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## Climate Science as a Profession

*Until the middle of the 20th century, the discipline of climatology was a stagnant field preoccupied with regional statistics representing a static “normal” climate. The study of climate change (what to many climatologists seemed a contradiction in terms) was only an occasional interest of individuals who worked in divergent ways, and scarcely knew of one another’s existence. It had little to do with meteorology, which itself was predominantly a craft that paid scant attention to physical theory. The Second World War and Cold War promoted a rapid growth of meteorology, which some practitioners began to combine with physical science in hopes of understanding global climate dynamics. But the dozen or so scientific disciplines that had something to say about climate were largely isolated from one another. In the 1960s and ‘70s, worries about climate change arose and began to push the diverse fields into contact. Scientists interested in climate change kept their identification with different disciplines but increasingly developed ways to communicate across the boundaries, for example in large international projects. Around the turn of the 21st century the Intergovernmental Panel on Climate Change institutionalized an unprecedented process of exchanges; its reports relied especially on computer modeling, which became a center of fully integrated interdisciplinary cooperation. (See also the essay on International Cooperation.)*

THE OLD CLIMATOLOGY - METEOROLOGY AND GEOPHYSICS (1940S-1950S) - FRAGMENTATION - CONFRONTING CLIMATE CHANGE (1960S-1970S) - MEANS OF COMMUNICATION (1970S-1980S) - COOPERATION AND INTEGRATION (1990S) - MATURITY AND ACTION (2001- )

“We cannot hope to understand the causes of climatic stability or change by restricting ourselves to any one field of earth science. Nature is ignorant of how our universities are organized...”  
— Peter Weyl<sup>1</sup>

### The Old Climatology

At the middle of the 20th century the professional study of climate was a scientific backwater. People who called themselves “climatologists” were mostly drudges who compiled statistics about weather conditions in regions of interest—the average temperatures, extremes of rainfall, and so forth. That could have offered a broad global perspective, but most climatologists set the planet as a whole aside and attended to regional problems. The people who needed climate information were farmers planning their crops and engineers designing dams or bridges.<sup>2</sup> This did not mean climatologists overlooked unusual weather, for it was precisely the decade-long

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<sup>1</sup> Weyl (1968), p. 60.

<sup>2</sup> For civil engineers demanding more data, see Genuth (1987), p. 244. A theory-heavy history of the climatology profession is Baker (2017).

drought or once-in-a-hundred-years flood that most worried the farmer or civil engineer. But people saw such catastrophes as just part of the normal situation, transient excursions within an overall state that looked permanent on the timescale of human society. The job of the climatologist was to remove uncertainties with statistics, fixing the probable size of a hundred-year flood and so forth.

Most historians of science have painted a different picture, focusing their writings on a handful of scientists in other fields who speculated about climate. Since ancient times many people wondered about gradual changes on a regional scale; starting in the mid nineteenth century the discovery of the ice ages and other great perturbations in the geological record raised questions about climate change on a global scale. The physical chemist Svante Arrhenius, the geologist T. C. Chamberlin, the engineer G. S. Callendar, and others took time away from their regular careers to publish works that were innovative and, given the broad range of their explanations, interdisciplinary. In retrospect these were pioneering contributions to the study of climate. A good many other scientists published speculations that are now justly forgotten. However, none of this was of much interest to people engaged in the professional discipline of climatology: their concern was the climate of the present.

Climatology had once been a pioneering field. Like most sciences it traced its roots to ancient Greece. The far-traveling Greek mariners and geographers had realized Earth is spherical and found it divided into different “climes,” from the frigid Arctic to the torrid tropics. A more complex picture emerged during the centuries of European exploration. In the early 19th century Alexander von Humboldt described how altitude and geography create zones where specific biological communities flourish, inspiring academics to map the varieties of climate in every part of the globe. They worked out detailed explanations for how the sunlight at a particular latitude, the characteristic winds and the mountain ranges that divert them, the currents shaped by the ocean basins, and so forth create regimes of temperature and precipitation—deserts, rainforests, tundra, and so on. The work was of more than scientific interest. Global climatology served imperialism, suggesting what types of crops and diseases a nation should plan for in a colony. By the middle of the twentieth century that job was largely completed. The frontiers of science had moved elsewhere, leaving behind a comfortably settled landscape.<sup>1</sup>

Typical was the situation at the U.S. Weather Bureau, where an advisory group reported in 1953 that climatology was “exclusively a data collection and tabulation business.”<sup>2</sup> Not much money or administrative attention was committed to such work, nor were the intellectual prospects enticing. To the extent that workers had research plans, their aim was just to find better ways to synthesize piles of data. A climatologist was somebody who *described* climate—mainly at ground level, where the crops and structures were found. These climatologists’ products were highly appreciated by their customers, and such studies continue to this day. Their tedious, painstaking style of scientific work would turn out to be indispensable for studies of climate

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<sup>1</sup> For 19th-century climate debates see Fleming (1998). Heymann and Achermann (2018).

<sup>2</sup> United States (1953), p. 24.

change. Still, scientists regarded the field (as one practitioner complained) as “the dullest branch of meteorology.”<sup>1</sup> Another expert remarked that in the study of climates, “the scientific principles involved are barely mentioned... Whether they are right or wrong does not seem to be of any moment, because they are never used to *calculate* anything.”<sup>2</sup>

When climatologists did try to go beyond statistics to explanations in terms of the angle of sunlight, the prevailing winds and ocean currents, and the like, the explanations used more hand-waving than equations. This was close to the field called physical geography, a matter of classifying climate zones with less interest in their causes than their consequences. If in the first half of the 20th century you looked in a university for a “climatologist,” you would probably find one in the geography department, not in a department of atmospheric sciences or geophysics (hardly any of the latter departments existed anyway). After all, the qualitative explanations of why a region had its particular climate were useless for telling farmers what they needed to know.

Attempts to make physical models of the simplest regular features of the planet’s atmosphere (for example, the trade winds) failed to produce any plausible explanation for how the winds circulated, let alone for variations in the circulation. This failure was hardly surprising, since meteorologists did not have an accurate picture of what they were trying to explain. Few measurements existed of the winds and moisture and temperature above ground level, and even ground-level data were scanty for vast portions of the globe. Most textbooks of climatology accordingly stuck to listing descriptions of the “normal” climate in each geographical zone, compiled by authors who, as one scientist complained, “know little, and care less, about mathematics and physical science.”<sup>3</sup>

Climatology could hardly be scientific when meteorology itself was more art than science. If the general circulation of the atmosphere was a mystery, still less could anyone calculate the course of storm systems. People had a variety of techniques for making crude weather forecasts. For example, while climatologists tried to predict a season by looking at the record of previous years, meteorologists similarly tried to predict the next day’s weather by comparing the current weather map with similar maps in an atlas of weather from the past. More often a forecaster just looked at the current situation and drew on his experience with a combination of simple calculations, rules of thumb, and personal intuition.

This craft had little to do with scientific advances. As one expert remarked ruefully as late as 1957, the accuracy of 24-hour weather forecasts had scarcely improved over the preceding 30 or 40 years. A canny amateur with no academic credentials could predict rain at least as successfully as a Pd.D. meteorologist, and indeed most of the “professionals” in the U.S. Weather Bureau

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<sup>1</sup> H. Lamb quoted in Alexander (1974), p. 90.

<sup>2</sup> For 19th-century origins of climatology, see Nebeker (1995), pp. 24-25; on the empiricism of the field, Eady (1957), quote p. 113, emphasis in original.

<sup>3</sup> Cressman (1996), pp. 382-85; “know little:” Stringer (1972), p. xii.

lacked a college degree. Aside from a handful of professors in a few pioneering universities (mostly in European geophysical institutes), meteorology was scarcely seen as a field of science at all, let alone a science firmly based on physics. Meteorology, one academic practitioner complained to another in 1950, “is still suffering from the trade-school blues.”<sup>1</sup>

Since the 19th century the forecasters and statistical climatologists had gone their separate ways. Neither group had much to do with the few professional academics, trained in physics, who from time to time attempted to analyze weather patterns with equations. Much of this work led nowhere and is now forgotten, but some laid the groundwork for later progress. Historians of science have naturally focused on the pioneering efforts of Vilhelm Bjerknes, L.F. Richardson, and others who developed the primitive equations that today form the foundation of scientific meteorology (see the essay on “General Circulation Models”). Based on fundamental physics, this work was by definition interdisciplinary. Through the first half of the twentieth century, however, these efforts had scant impact on most of the people whose careers lay in the discipline of meteorology.

Some hoped that climate, averaging over the daily vagaries of weather, might be more amenable to scientific investigation. They tried to understand changes on a timescale of decades or centuries, and searched for regular climate cycles. While a few looked for possible physical causes, it was more common for a climatologist to avoid such speculation and carry out grinding numerical studies in hopes of pinning down recurrences and perhaps predicting them. Analysis of large sets of data turned up various plausible cycles, correlated perhaps with variations in the number of sunspots. These correlations invariably turned out to be spurious, further lowering the poor reputation of climate change studies.

The stagnant condition of climatology mirrored a deep belief that climate itself was basically changeless. The careers of climatologists—their usefulness to society—rested on the conviction that statistics of the past could reliably describe future conditions. Their textbooks *defined* “climate” as the long-term average of weather over time, an intrinsically static concept. As one practitioner later complained, “authoritative works on the climates of various regions were written without allusion to the possibility of change, sometimes without mention of the period to which the quoted observations referred.”<sup>2</sup> In part this approach reflected a simple absence of data. There were hardly any accurate records of daily temperatures, seasonal rainfall, and the like that went back more than half a century or so, even for the most civilized regions. The records were scantier still for less-developed countries, and mere fragments for the three-quarters of the world covered by water and ice. It seemed reasonable to assume that the existing records did reflect the average weather over at least the past few thousand years. After all, historical records back to

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<sup>1</sup> Accuracy not improved: Mason (1957), p. 175, see p. 183; Koelsch (1996); College degrees: Byers (1976), p.1343. “Blues”: George Platzman to Jule Charney, 18 June 1950, Box 14:451, Charney Papers, Massachusetts Institute of Technology Archives, Cambridge, MA. On the low professional status of U.S. meteorology see Harper (2006).

<sup>2</sup> Lamb (1959), p. 299.

ancient times showed much the same mixtures of frosts and rains, and the crops that went with them, in a given region.

In fact, history gave only the crudest indications. But climatologists scarcely recognized their ignorance, relying explicitly or implicitly on old assumptions about the stability of nature. In other sciences like geology, experts found good reason to maintain that natural processes operated in a gradual and uniform fashion. Ordinary people too mostly believed that the natural world was self-regulating. If anything perturbed the atmosphere, natural forces would automatically compensate and restore a self-sustaining “balance.”

To be sure, at least one immense climate change was known and cried out for investigation—the ice ages. The stupendous advances and retreats of continental ice sheets were worth study, not because scientists thought it was relevant to modern civilization, but because they hoped to snatch the brass ring of prestige by solving this notorious puzzle. Both professionals and amateurs advanced a variety of simple explanations. Most of these amounted to no more than vague but plausible-sounding arguments presented in a few paragraphs. Each expert defended a personal theory, different from anyone else’s. The few scientists who attempted to write down equations and calculate actual numbers for the effects managed to prove little, except at best that their ideas were not wildly astray by orders of magnitude.

The most acceptable explanations for the ice ages invoked geological upheavals to block ocean currents or raise a mountain range against prevailing winds. This was necessarily an interdisciplinary sort of theory. “It is impossible to separate the geological from the meteorological,” as one meteorologist remarked, “as the two are expressions of the results of the same forces.”<sup>1</sup> But the many pages that scientists wrote amounted only to elaborate hand-waving, unsatisfactory within either field. “I, for one,” said the respected climatologist Hubert H. Lamb, “must confess to having been bewildered and left quite pessimistic by some discussions of climatic variation.”<sup>2</sup> The very concept of “theory” became suspect in climate studies.

Theoretical models, whether of climate stability or ice-age changes, were usually pursued as a minor sideline when they were not just ignored. To study “the climate” of the planet as a whole was far less useful and promising than to study “climates” region by region. There was little point in attempting global calculations when all the premises were uncertain and key data were lacking. Given the enormous obstacles to reaching reliable results, and the prevailing view that the global climate could not possibly change on a timescale that would matter except to far future generations, what ambitious scientist could want to devote years to the topic?

## Meteorology and Geophysics (1940s-1950s)

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<sup>1</sup> Napier Shaw in discussion of Harmer (1925), p. 258.

<sup>2</sup> Lamb (1959), p. 4.

Yet it is the nature of scientists never to cease trying to explain things. A few people worked to lift meteorology and climatology above the traditional statistical approach. Helmut Landsberg's 1941 textbook *Physical Climatology* and a 1944 *Climatology* textbook written by two other meteorologists demonstrated how familiar physical principles underlay the general features of global climate, and provided a rallying-point for those who wanted to make the field truly scientific. Many saw such studies as an exercise in pure mathematics, deliberately remote from the fluctuations of actual weather. As one scientist recalled, in the 1940s, "academic meteorologists would sometimes go out of their way to disclaim any connection with forecasting—an activity of dubious scientific standing."<sup>1</sup>

The climatology textbooks nevertheless came into use during the Second World War as meteorology professors trained recruits to support military campaigns with both short-term forecasts and long-range planning. This was largely the work of a group at the University of Chicago, where in 1942 Carl-Gustav Rossby had created a department of meteorology. Rossby was a Swede who had learned mathematical physics in Stockholm and spent two years at Bjerknæs's institute in Bergen, Norway. It was in Bergen that some of the key concepts of meteorology had been discovered, notably the weather "front" (first recognized during the First World War and named in accord with the concerns of the time).<sup>2</sup> With their improved understanding of weather patterns, Bjerknæs's group had come to think of climate not so much in geographical terms as a matter of latitudes and locations, but in terms of typical weather systems. And if the pattern of weather systems in a region changed, didn't that mean a change of climate? It was a new way of looking at things, a "dynamical climatology" as one of the Bergen group put it.<sup>3</sup>

One force behind this conceptual change was the rise of aviation, which from the First World War onward encouraged studies of the upper atmosphere. Weather services took to regularly launching balloons to measure what was happening above. This "conquest of the third dimension" (as one meteorologist called it) not only helped with weather prediction but brought a better understanding of the general circulation of the atmosphere. Seeing the atmosphere in depth encouraged turning from the static two-dimensional maps of classical climatology to a concept of climate as the product of the global atmosphere as a dynamical whole.

Rossby, the central figure in the new way of thinking, had come to the United States in 1925 to work in the Weather Bureau. Outstanding not only as a theorist but also as an entrepreneur and organizer, Rossby soon left the somnolent Bureau. In 1928 he created the nation's first professional meteorology program at the Massachusetts Institute of Technology. After his move to Chicago he did still more, thanks to the ample wartime support for training military

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<sup>1</sup> Landsberg (1941, rev. ed. 1947, 1960), see the preface, p. iii; On the book's importance: Taba (1991), p. 97; Haurwitz and Austin's *Climatology* (and also Rossby) are noted by Smagorinsky (1991), p. 30; "academic... dubious": Sutcliffe (1963), p. 277.

<sup>2</sup> Friedman (1989).

<sup>3</sup> Heymann (2010).

meteorologists. His department trained some 1,700 people in one-year courses. Rossby also helped coordinate new programs for graduate training of meteorologists at several other American universities.<sup>1</sup>

The wartime programs gave a big boost to the few universities where scientific meteorology already existed, and led to further expansion after the war. One example was the young geology student Reid Bryson, who was picked up by the Air Force and trained in weather forecasting. After the war he got a Ph.D. in meteorology and, finding himself unwelcome in the geography department at the University of Wisconsin, founded a one-man meteorology department there. In 1962 the National Science Foundation gave him funds to establish an important climate research center.<sup>2</sup> Another example was Edward Lorenz, who had intended to be a mathematician but was diverted into meteorology during the war, when the Army Air Corps put him to work as a weather forecaster. Bryson and Lorenz were among “a new breed of young Turks” who broke away from the tradition of climatology as a mere handmaiden to forecasting. (At any rate, that was how they saw themselves in retrospect.)<sup>3</sup>

Support for anything connected to meteorology expanded after the war as the Cold War and the vigorous economy—especially the rapid growth of civil aviation—raised the demand for meteorologists. The Chicago group flourished. It was the first group anywhere to systematically develop physical models of climate, sending out numerous students to carry on the approach elsewhere. Meteorology began to gain a reputation in the United States (as it already held in Europe) as a true scientific discipline, and climatology followed. As Rossby remarked a few years later, basic questions of climate change, such as storage of heat in the oceans or the level of carbon dioxide gas in the atmosphere, “mean a completely new class of questions... In these investigations one is hardly interested in geographical distributions.” Unlike the traditional regional climatologists, his group looked at the entire planet as a physical system.<sup>4</sup>

War-trained young meteorologists also moved into the U.S. Weather Bureau, where they found “the stuffiest outfit you’ve ever seen,” as a member of the research-oriented new generation later recalled—“deadly, deadly dull... a backward outfit.” An official report complained in 1953 that “the Bureau has displayed an arbitrary and sometimes negative attitude toward new developments in meteorology originating outside the Bureau.” To be sure, inside the Bureau and still more outside it, meteorology was incorporating important new approaches such as weather radar, radiosondes to measure the upper atmosphere, and attention to the “air mass” analysis introduced by the Bergen school. And partly in response to the negative reports, conditions in the Bureau were improving rapidly. But as for climatology at the Bureau, in 1957 another report

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<sup>1</sup> “Conquest:” Hermann Flohn (1951) as quoted by Heymann and Achermann (2018), p. 608, q.v. for all these developments. Here and below I am grateful for the use in draft of Doel (2003). Rossby: Fleming (2016).

<sup>2</sup> Bryson (1967), and personal communication, 2002.

<sup>3</sup> Koelsch (1996); “Turks”: Smagorinsky (1991), p. 31; Nebeker (1995), ch. 9.

<sup>4</sup> Byers (1959); Rossby (1959), quote p. 16. Reputation: Harper (2006).

described it as still nothing but a mere passive “subsidiary to the task of forecasting.” Other institutions devoted to climatology were equally stodgy.<sup>1</sup>

Stagnation was unacceptable to those who recalled the invaluable contributions of meteorology to military operations during the war. The armed forces thought it no less important for their postwar global operations, even if the Cold War stayed cold. And if nuclear bombs exploded, meteorology would be especially vital for tracking the deadly fallout. The Navy and Air Force in particular continued to employ many hundreds of meteorologists. Besides, in keeping with the new respect for science that they had learned during the war, the armed forces supported a variety of academic researchers whose studies might ultimately make forecasting better. As for climate, some of these researchers held out the fascinating prospect of changing it deliberately, perhaps as a weapon. The advances that meteorology was making toward solid scientific understanding, combined with the lavish Cold War funding for all science, made for a rapid expansion and professionalization of climatology.

It helped that the entire area of geophysics, which included most of the fields relevant to climatology, was becoming stronger and better organized. Since early in the century there had been a few institutions, notably university institutes in Germany, that embraced a wide enough range of studies to take the name “geophysical.” Already in 1919 an International Union of Geodesy and Geophysics was founded, with separate sections for the different fields such as terrestrial magnetism and oceanography. An American Geophysical Union was also created in 1919 as an affiliate of the U.S. National Academy of Sciences (it would not become an independent corporation with an international membership until 1972). There followed a few other national societies and journals such as the *Zeitschrift für Geophysik*. Several German universities created formal programs teaching “*Geophysik*.”

As a founder of the International Union remarked, it was not so much a union as a confederation.<sup>2</sup> The other early professional organizations likewise brought little cohesion. Through the 1920s and 1930s, very few institutions of any kind addressed geophysics in a broad sense. Most individuals who might be called geophysicists did their work within the confines of one or another single field such as geology or meteorology. In the scientific investigation of climate change, when I look over the more significant publications—or at any rate the ones I have used as references in the present study, found in the bibliography—a great variety of books and journals turn up. The only ones that stood out from the crowd in this period were the *Quarterly Journal* and *Memoirs* of Britain’s Royal Meteorological Society, which together published 18% of the pre-1940 journal articles I have cited. The runner-up was the *Journal of Geology*, with 9%.

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<sup>1</sup> “Stodgiest”: Athelstan Spilhaus, interview by Ron Doel, November 1989, AIP; see also Joseph Smagorinsky, “Climate’s scientific maturity,” in Baer et al. (1991), pp. 29-35, 31; “arbitrary:” United States (1953), p. 36, see pp. 3-4; “subsidiary:” National Academy of Sciences (1957); stodgy climatology in general: Lamb (2002).

<sup>2</sup> L.A. Bauer quoted in Good (2000), p. 286, q.v. for this topic in general.



Beginning in the late 1940s, a more significant number of inclusive institutions appeared. Institutes of geophysics were created at American universities and under the Soviet Academy of Sciences, along with funding organs like the Geophysics Research Directorate of the U.S. Air Force. Another big boost came in 1957-58 when the International Geophysical Year pulled together thousands of scientists from many nations. They interacted with one another in committees that planned, and sometimes conducted, interdisciplinary research projects involving a dozen different “geophysics” fields.<sup>1</sup> Most of these fields were relevant to climatology.

The annual meetings of the American Geophysical Union became a rendezvous for diverse fields, and for the same purpose the Union began publishing a *Journal of Geophysical Research* (expanded from the older and narrower *Terrestrial Magnetism*). However, for the scattered scientists engaged with climate change, the best meeting-place was *Tellus*, a “Quarterly Journal of Geophysics” that the Swedish Geophysical Society created in 1949. The journal’s importance is evident in the list of papers that found their way into the bibliography that I compiled in my research for this study. During the decades 1940-1960, *Tellus* published some 20% of these papers, more than any other journal. (The runners-up were the American interdisciplinary journal *Science*, with 15%, the *Journal of Meteorology*, with 10%, and the *Quarterly Journal of the Royal Meteorological Society*, with 5%. The *Journal of Geophysical Research* accounted for only 3%, about equal to the *American Journal of Science* and the *Journal of Geology*.)

Some two-thirds of these papers were written in the United States—a much higher fraction than for earlier years.<sup>2</sup> This was partly because the rest of the civilized world spent the 1950s recovering from the war’s devastation. It was still more because generous U.S. government support for geophysical research, based on Second World War successes, did not falter even when memories of the war faded. For the global military and economic concerns of the Cold War put geophysics near the head of the line for research funds.

## Fragmentation

In geophysics as in all the sciences of the 20th century, expansion raised a risk of further fragmentation. Early in the century, so little had been known about anything in geophysics that the best scientists had broad knowledge of many aspects of the subject. For example, between the world wars Harald Sverdrup published research on the circulation of the atmosphere, the circulation of the oceans, glaciers, geomagnetism, and the tides, not to mention the ethnology of Siberian tribes. A few decades later, when knowledge had grown deeper and techniques had become more esoteric, hardly anyone could do significant work in more than one or two fields.

It was getting ever tougher for a scientist to become expert in a second field of knowledge. Few now attempted it, for the diversion of energy risked your career. “Entering a new field with a degree in another is not unlike Lewis and Clark walking into the camp of the [Native American]

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<sup>1</sup> Doel (1997); Doel (1998).

<sup>2</sup> My rough count from a sample.

Mandans,” remarked Jack Eddy, a solar physicist who took up climate studies in the 1970s. “You are not one of them... Your degree means nothing and your name is not recognized. You have to learn it all from scratch, earn their respect, and learn a lot on your own.”<sup>1</sup> Some of the most important discoveries came from people like Eddy, who did spend years in a foreign camp. Another example was Nick Shackleton, who after studying physics (essential for laboratory work measuring isotopes) and mathematics (necessary for analysis of time series) became part of a research group that analyzed pollen in a university botany department. The eventual result was landmark work on the timing and nature of the Ice Ages.<sup>2</sup> Such combinations, however valuable, were uncommon.

The problem was particularly severe for climate studies. There had never been a community of people working on climate change. There were only individuals with one or another interest who might turn their attention to some aspect of the question, usually just for a year or so before returning to other topics. An astrophysicist studying changes in solar energy, a geochemist studying the movements of radioactive carbon, and a meteorologist studying the global circulation of winds, had little knowledge and expertise in common. Even within each of these fields, specialization often separated people who might have had something to teach one another. They were unlikely to meet at a scientific conference, read the same journals, or even know of one another’s existence. Nor did theorists interact regularly with people who worked out in the field. As one climate expert remarked, “lack of interest has all too often characterized the attitude of physical scientists to the masses of information produced by botanists examining pollen deposits and the data turned out by geologists, glaciologists, entomologists, and others. These types of literature have never been part of their regular diet.”<sup>3</sup>

To make communication still harder, different fields attracted different kinds of people. If you went into the office of a statistical climatologist, you could expect to find ranges of well-organized shelves and drawers stacked with papers bearing neat columns of figures. In later years the stacks would hold computer printouts, the fruit of countless hours spent coding programs. The climatologist was probably the kind of person who, as a boy, had set up his own home weather station and meticulously recorded daily wind speed and precipitation, year after year. Go into the office of an oceanographer, and you were more likely to find a jumble of curiosities from the shores of the seven seas. You could hear adventure stories, like Maurice Ewing’s tale of how he was washed overboard and escaped drowning by a hair. Oceanographers tended to be salty types, accustomed to long voyages far from the comforts of home, outspoken and sometimes self-centered.<sup>4</sup>

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<sup>1</sup> J.A. Eddy, interview by Weart, April 1999, AIP, p. 4.

<sup>2</sup> Shackleton (2003).

<sup>3</sup> Lamb (1997), p. 200.

<sup>4</sup> For strains on deep-ocean oceanographers, see Mukerji (1989), pp. 66-73; Ewing: Wertenbaker (1974), pp. 130-33.

These differences went along with divergence in matters as fundamental as the sorts of data people acquired and used. The economic importance of weather forecasting meant that climatologists could draw on a century-old and world-wide network of weather stations. “Meteorologists use mainly standard observations made by technicians,” as an oceanographer recently remarked, “while the much smaller number of oceanographers usually make their own measurements from a small number of research ships,” often with instruments they had built for themselves.<sup>1</sup> The climatologist’s weather, constructed from a million numbers, was something entirely different from the oceanographer’s weather—a horizontal blast of sleet or a warm relentless trade wind.

On top of social and perceptual gaps were technical divergences. As one expert remarked in 1961, “The fact that there are so many disciplines involved, as for instance meteorology, oceanography, geography, hydrology, geology and glaciology, plant ecology and vegetation history—to mention only some—has made it impossible to work... with common and well established definitions and methods.” Scientists in different fields might use standards so different, he said, “that comparisons between the results have been hardly possible.”<sup>2</sup>

Recognizing the problem, meteorologists made significant efforts to recruit students from various fields of the physical sciences and to initiate interdisciplinary work. Physics, chemistry, and mathematics played an increasing role in what was coming to be called the “atmospheric sciences.” A *Journal of the Atmospheric Sciences* had been founded already in 1944. As one example of how the process went still farther, in 1961 Chicago’s pioneering Department of Meteorology merged with the Department of Geology to form a Department of the Geophysical Sciences. Yet up to this point the discipline of meteorology itself had remained to a large degree divided. The climatologists who continued to gather empirical weather statistics and analyze them were intellectually remote from the academic theorists, who worked up mathematical models based on physical principles rather than observations. Both often looked down on practical forecasters, who in turn had little faith in the professors’ abstractions. Among all three types of meteorologist, very few worked on questions of long-term climate change.<sup>3</sup>

## Confronting Climate Change (1960s-1970s)

Fragmentation was becoming intolerable by the 1960s. More than half a century of reliable temperature measurements were now in hand from around the world, and they showed that global temperatures had risen. Meanwhile observations of the climbing level of carbon dioxide in the atmosphere brought a threat of serious future changes. Besides, scholarly studies that extended the climate record far into the historical past were revealing large climate shifts. Most

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<sup>1</sup> Indeed “meteorology and oceanography are practiced in a very different manner and by two largely non-overlapping groups of people... there are still relatively few meteorologists who have more than a superficial knowledge of the ocean, and vice versa.” Charnock (1998), p. 623.

<sup>2</sup> Wallén (1963), p. 467.

<sup>3</sup> Nebeker (1995), pp. 1-2.

notable was evidence of a century or so of exceptional warmth in parts of medieval Europe and the North Atlantic (this was when the Vikings settled Greenland). There had followed winters so harsh that early modern times could be called a “Little Ice Age”—at least in some regions. Records were spotty, at best, for the world outside the North Atlantic region, but for many places evidence was emerging of anomalies such as centuries of prolonged drought.

Painful experience drove the point home. One notorious case was the experience of firms that contracted to build dams in central Africa in the 1950s, and consulted with climatologists about the largest floods that could be expected according to past statistics. The firms then began construction, only to suffer “fifty-year floods” in each of the next three years.<sup>1</sup> Such experiences pulled the props out from the traditional climatology. The laboriously compiled tables of past statistics were plainly not reliable guides to the future.<sup>2</sup>

This unhappy fact was not easily accepted. As late as 1968, a textbook on *Climatology and the World's Climate* said baldly, “The subject of climatic change is not given specific treatment in this book.”<sup>3</sup> Applied climatologists continued to base their projections of the future on their hoards of old statistics, simply for lack of anything better. Their work was in fact becoming increasingly useful. As the data base grew and methods of analysis expanded, climatological studies brought a better understanding of how warm spells affected crops, what factors contributed to floods, and so forth.<sup>4</sup> Nevertheless, during the 1960s more and more scientists realized that climate predictions could not rely only on past observations, but must use physical models and calculations. Traditionally “climate” had been defined as the weather in a region averaged over a period. For example, in 1935 the International Meteorological Organization had adopted the years 1901-1930 as the “climatic normal period.” A moving thirty-year span became accepted as a baseline for predictions of future climates. But experts increasingly saw that this practice, however necessary to provide answers to pressing questions, could be misleading. The weather of the first three decades of the century turned out to have been far from what was “normal” in later decades. Indeed there might be no such thing as a set of decades that could define a “normal” climate. Climate was something that changed continually under the impact of physical forces.<sup>5</sup>

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<sup>1</sup> Floods: Lamb (1997), p.178, see passim for historical work.

<sup>2</sup> Lamb (1959); Lamb (1966a), p. ix.

<sup>3</sup> Rumney (1968), p. vii; in another widely used text, a chapter on climate change first appeared, with a new author, in 1980 (the fifth edition): Trewartha and Horn (1980).

<sup>4</sup> Cressman (1996).

<sup>5</sup> I have seen only one explicit statement about this at the time (“we are faced with an initial difficulty of definition which has far-reaching consequences...”), Robinson (1971), p. 12; similarly but implicitly, Barrett and Landsberg (1975), p. 18. The U.S. Weather Bureau published climate “normal” averages for the United States based on 1901-1930 in 1931 and every ten years thereafter. For the history see Lamb (1995), pp. 10-11.

The new thinking was displayed in full at a 1965 symposium held in Boulder, Colorado on “Causes of Climate Change.” While the meeting made little special impression at the time, in retrospect it was a landmark. For it deliberately brought together scientists from a fantastic variety of fields, experts in everything from volcanoes to sunspots. Presiding over the meeting was an oceanographer, Roger Revelle. (Oceanography would play an especially central role among the tangle of specialties, for the oceans are a main engine of world climate, storing and moving most of the heat in the entire system; the study of climate change would stall unless the new atmospheric science could be married with a new global oceanography, likewise built out of basic physics equations.)

At the Boulder meeting lectures and roundtable discussions boiled with spirited debate as rival theories clashed; Revelle needed all his exceptional leadership skills to keep the meeting on track. Convened mainly to discuss explanations of the ice ages, the conference featured a burst of new ideas about physical mechanisms that could bring surprisingly rapid climate shifts. In his formal summary of the discussions, the respected climatologist Murray Mitchell reported that our “comparatively amicable interlude” of warmth might give way to another ice age, and sooner than had been supposed. That foreboding possibility required scientists to understand the causes of climate change, he said, and to suggest how we might use technology to intervene.<sup>1</sup>

This sort of thinking spread widely in the early 1970s. A spate of devastating droughts and other weather disasters showed that climate was grossly unreliable. With the alarming news came warnings that the near future might see still worse—whether drastic cooling or global warming—thanks to pollution of the atmosphere following the explosive growth of human population and industry. This was an active and even aggressive view of climate in relation to humanity; it called for aggressive research. “The old descriptive climatology,” an authority remarked in 1975, “concerned mainly with statistics and verbal interpretation of them, is evolving into a new mathematical, or dynamic, climatology with predictive capability based on physical-mathematical processes rather than extrapolation of statistical measures.”<sup>2</sup>

That required a new kind of research community, more closely linked to other fields and other kinds of science. This was happening in all the Earth sciences. The traditional observational geologist, out in the field with his high-laced engineer’s boots and rock hammer, had to make room for the investigator who saw rocks mainly in her laboratory, or perhaps only in pages of equations and calculations. Old-school geologists grumbled that the move to laboratory and theoretical geophysics took people away from a personal confrontation with nature in all its complexity and grandeur. The same filtering of experience was spreading in climate studies. Most scientists with something to contribute focused on technical problems peculiar to their own specialty. How do aerosols make clouds? How can you get a computer model to show the annual cycle of the seasons? What was the pattern of ancient glacial cycles? Those who did attack

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<sup>1</sup> Mitchell, “Concluding Remarks,” drawing on the remarks by Roger Revelle, in Mitchell (1968), p. 157, see also pp. iii-iv.

<sup>2</sup> Barrett and Landsberg (1975), p. 76; see Lamb (1995), pp. 12-14.

broader questions head-on seemed out of date. Some continued to propose simple hand-waving models with physical explanations for climate change (especially the ice ages). But the different explanations were patently speculative, infected by special pleading and mostly incompatible with one another.

Scientists were more skeptical than ever of the traditional approach, in which each expert championed a favorite hypothesis about some particular cause for climate change—blaming every shift on variations in, say, dust from volcanoes or the Sun’s luminosity. It seemed likely that many factors contributed together. Meanwhile the factors were interacting with one another. And on top of these external influences, it appeared that some part of climate change was self-sustaining, through feedbacks involving the atmosphere, ice sheets, and ocean circulation. “It is now generally accepted,” wrote one authority in 1969, “that most climatic changes... are to be attributed to a complex of causes.”<sup>1</sup>

The shortcomings of the old single-cause approach were especially visible to those who tried to craft computer models of climate. A plausible model could not be constructed, let alone be checked against real-world data, without information about a great many different kinds of things. It became painfully clear that scientists in the various fields needed one another. Specialists began to interact more closely, drawing on one another’s findings or, equally valuable, challenging them. It was the stringent requirements of numerical computation, more than anything else, that forced the isolated communities of meteorology—empirical climatologists with their statistics, weather forecasters with their practical intuition, academic scientists with their theories and equations—to communicate with one another in a common enterprise, and beyond that to talk with other scientists of every stripe.

## Means of Communication (1970s-1980s)

The changes in meteorology and geophysics were typical of a movement in all the sciences. For more than a century many fields of science had narrowed their perspective to simplified cases, pursuing solutions as compact and elegant as Newton’s equations. Subjects as far afield as sociology were swayed by what some began to call “physics envy.” Only a few scientists insisted on looking instead at whole systems with all their complexities. That approach began to spread in various fields during the postwar years, and a growth spurt in the 1970s brought into prominence what was coming to be called “holistic” investigation. In biology, for example, different disciplines were talking to one another within the increasingly popular field of ecology. This was timely, for scientists were increasingly concerned that biological communities were yet another feature that interacted intimately with the planet’s climate. Some specialists had long been aware of such interactions—most notably in oceanography, which was explicitly a union of physical oceanography and biological oceanography (if only because the researchers had to bunk alongside one another on their voyages). Now all of geophysics was coming to be seen as part of a larger field, the “Earth sciences.”

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<sup>1</sup> Lamb (1969), p. 178.

In the fields relating to climate, as in other sciences, textbooks and review articles in ever growing numbers summarized the recent findings of this or that specialty for the benefit of outsiders. More and more conferences were held with the aim of bringing together anywhere from a dozen to several hundred people from different but relevant fields. Most scientists, however, continued to call themselves oceanographers or computer scientists or paleobotanists or whatever. Not many would identify themselves as primarily a.... a what? A “climate change scientist?” There was not even an accepted term to describe the non-discipline. The typical landmarks for the creation of a discipline, such as departments at universities or a scientific society named for the subject, never came. The key elements for any profession—socialization and employment, which for scientists usually meant training as a graduate student and employment as a professor—were largely carried out within traditional disciplines like meteorology or oceanography, or in more broadly defined fields such as atmospheric sciences in which climate change was included only as one element among many.

In 1977, one landmark for the recognition and coalescence of a scientific discipline did come with the foundation of a dedicated journal, *Climatic Change*. But unlike many new journals, this one did not in fact launch itself as the flagship of a new discipline. Its explicit policy was to publish papers that were mainly interdisciplinary, such as explorations of the consequences that global warming might have on ecosystems. The founding editor, Stephen Schneider, said later that he took up the task “to spite my institute director,” who had warned him that pursuing interdisciplinary work would hurt his career. Many scientists believed that solid research could be done only within the strict framework of a traditional discipline.<sup>1</sup>

Most scientific papers on climate change itself continued to be published in journals dedicated to a particular established discipline, like the meteorologists’ *Journal of the Atmospheric Sciences* or the paleontologists’ *Quaternary Research*. But key papers were also welcomed by the two great interdisciplinary scientific journals, *Science* and *Nature*, where specialists in every field would see them. (In my bibliography for 1960-1980, *JAS* published 10% of all papers and *Quat. Res.* 7.5%. *Science* published 23%, if one includes a few news articles, and *Nature* 10%. *Tellus* was down to 5%, equal to the *J. Geophysical Research*, followed by the *Journal of Applied Meteorology* at 4%. The *Quart. J. Royal Met. Soc.* fell to 2.5%.)

To a degree, climate science remained “a scientific backwater,” as one of its leading figures recalled decades later. “There is little question,” he claimed, “that the best science students traditionally went into physics, math and, more recently, computer science.”<sup>2</sup> The study of

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<sup>1</sup> Policy: Schneider (1991). Schneider (2009), pp. 75-76. N.b. in 1983 the *Journal of Applied Meteorology* became the *Journal of Climate and Applied Meteorology*, absorbed in 1988 into the *Journal of Climate*, which had begun in 1986.

<sup>2</sup> The claim was made to warn policy-makers about the unreliability of climate predictions, but it is plausible. Richard Lindzen, Testimony before the Senate Environment and Public Works Committee, May 2, 2001, available as appendix to United States Congress (107:1) (2001).

climate was not a field where you could win a Nobel Prize or a million-dollar patent. You were not likely to win great public fame, nor great respect from scientists in fields where discoveries were more fundamental and more certain. In the mid 1970s, it would have been hard to find a hundred scientists with high ability and consistent dedication to solving the puzzles of climate change. Now as before, many of the most important new findings on climate came from people whose main work lay in other fields, from air pollution to space science, as temporary detours from their main concerns.

Coordination and communication nevertheless improved as climate science was swept along by changes in the sciences as a whole. During the 1960s and 1970s, governments doubled and redoubled the budgets for every field of research, and geophysics got its share. Scientists concerned about climate change worked to get governmental and international agencies to organize their diverse research efforts through a central office or committee. It took decades of failures and false starts, but by the end of the 1970s, they managed to put together a number of ambitious climate programs. While still lacking central coordination, each of the programs embraced a variety of fields. In particular, the United States established a National Oceanic and Atmospheric Administration that united oceanography with meteorology in a formal institutional sense, even if the usual bureaucratic barriers remained between divisions. Meanwhile within NASA, where designing satellites to observe the Earth from space gave a push to broader views, some worked deliberately to break down disciplinary boundaries and create an “Earth System Science.”<sup>1</sup> Specialists in diverse fields with an interest in climate change found themselves meeting in the various committees and panels that reviewed and directed such programs. The process was officially capped in the mid 1980s by the creation of an “International Geosphere-Biosphere Program,” which coordinated work across so many disciplinary boundaries that some began to worry that there were now too many cooks in the kitchen.

The researchers in such programs no longer spoke of studying “climates” in the old sense of regional weather patterns, but of “the climate system” of the whole planet, involving everything from minerals to microbes. This was a fundamentally novel approach. We could call it a new “paradigm,” in the word’s basic sense of a pattern (like the *amo*, *amas*, *amat* of Latin grammar texts) that scientists used to structure their thinking as they attacked their research problems. Many things contributed to the new approach, but nothing so much as the computer studies that began producing plausible climate models during the 1970s. The models spoke eloquently of a global system in their basic concepts, and showed it memorably in their computed maps of weather patterns.<sup>2</sup>

For studying a system with features dispersed among many specialties, the solution was collaboration. This trend was strong in all the sciences, as research problems spanned ever more complexities. Scientists with different types of expertise exchanged ideas and data, or worked

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<sup>1</sup> Conway (2008).

<sup>2</sup> The term “paradigm” has multiple meanings in the classic Kuhn (1962); for this particular usage, see Weart (1983). Edwards (2001).



directly together for months if not years. Universities and other institutions, braced by ample funding, increasingly encouraged coalitions of research groups in a variety of fields. Specialists in the ionosphere, the Earth's interior, ocean currents, even biology, found themselves sharing the same funding agencies, institutions, and perhaps buildings. Sessions bringing together different specialists on one or another climate topic multiplied at meetings of the American Geophysical Union and similar organizations. It became increasingly common to hold entire workshops, meetings or conferences devoted to a particular interdisciplinary topic.

Perhaps most important, every scientist read *Science* and *Nature*, which competed with one another for outstanding papers in all fields, including those connected with climate change. Both these weekly journal-magazines also published expert reviews and commentaries, and *Science* published staff-written news articles, keeping everyone up-to-date on selected developments outside their own field.

By 1980 progress in computer models and other areas had brought a convergence of scientific opinion. Nearly all experts now agreed that there was at least a serious possibility of dangerous global warming. None would commit themselves to saying how certain this was. If the models were correct, the warming would become unequivocally apparent around the start of the next century. By then it would be too late to prevent damage. The research agenda was clear: find out how much warming was really likely to happen.

An especially powerful mechanism for cooperation was the formation of projects to address particular interdisciplinary topics. One example of many: specialists in computer modeling got together with paleontologists to test whether the models were robust enough to simulate a climate different from the present one. The Cooperative Holocene Mapping Project (COHMAP) was conceived in the late 1970s at the University of Wisconsin, where Reid Bryson had established a group that reconstructed past climates from fossil pollen and the like. The project expanded through the 1980s, recruiting a variety of domestic and foreign collaborators. Some of them would devote most of their research careers to the project. Typical of such projects, all the collaborators would convene from time to time in large assemblies. But a few leaders would also gather in smaller meetings, "often hosted in home settings where conversations were unhurried and brainstorming was lively." Computer models confronted paleontological data in a continual dialogue, each discrepancy forcing one side or the other, or both, to go back and do better. (Ultimately the modelers produced a good simulation of the climate maps that the paleontologists developed for a warm period 8,000 years ago.)

Most interdisciplinary projects driven by the demands of modelers, who sought empirical data on a scale to match the floods of numbers gushing from their computers. Large modeling groups in the United States, Great Britain, Germany, and elsewhere, pursuing empirical data to validate and correct their work, inspired costly projects in specialties ranging from satellite instrumentation to oceanography to forestry. Traditional climatology with its vast archives of data helped with its

own major projects of analysis and synthesis. *For other international projects see the essay on International Cooperation.*<sup>1</sup>

The steep climb of concern about global warming in scientific, public, and official circles did not translate into any exceptional increase of funding in the 1980s. Particularly in the United States, the world's largest source of money for research, the Reagan administration instinctively disbelieved all claims supported by environmentalists. Moreover, during the 1980s most of the industrialized countries, from the United States through Western Europe to the Soviet Union, failed to increase their research spending. With jobs in research scarcer than applicants, few students were attracted to the grueling labor of winning a PhD in a field like meteorology. Nevertheless, climate change managed to attract an increasing number of students and grants, rising at least as rapidly as other important fields of science in the 1980s. After stalling in 1970-1975 the annual number of scientific papers published on climate change world-wide began again to rise in a fairly smooth exponential, more than doubling each decade.<sup>2</sup>

Climate research remained quite a small field of science in the 1980s. Whereas any substantial sub-field of physics or chemistry counted its professionals in the thousands, the number of scientists dedicated full-time to research on the geophysics of climate change was probably only a few hundred worldwide. (If you included every scientist competent to at least comment on some aspect, including such fields as biological responses to climate change, it would still be not much above a thousand.)<sup>3</sup> Since these climate scientists were divided among a great variety of fields, any given subject could muster only a handful of true experts. They knew each other well, by reputation and often personally.

## Cooperation and Integration (1990s- )

Projects with multiple contributors were becoming common in all the sciences, a consequence of the increasing specialization within each discipline plus increasing value in making connections between disciplines. Versatile scientists like Sverdrup—or as another example Bert Bolin, who had mastered fields ranging from the mathematics of atmospheric circulation to the geochemistry of CO<sub>2</sub>—were a vanishing breed. Nearly all the papers written before 1940 in my bibliography were published under a single name; only a few were the work of two authors. But of papers written in the 1980s, fewer than half had one author. Many of the rest had more than two, and a paper listing, say, seven authors was no longer extraordinary. Large projects were represented by,

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<sup>1</sup> Webb (2007), quote p. 107; see also comments in this volume by Kutzbach, p. 224, and Sandy P. Harrison, p. 168.

<sup>2</sup> From 76 papers in 1975 to 447 in 1997, Stanhill (1999).

<sup>3</sup> Estimate of 200 to 300: Gee (1989). The IPCC study in 1995, aiming at comprehensive international inclusion, had about 500 “authors” and over 500 “reviewers” who submitted suggestions.

for example, a 1989 paper with 20 authors from 13 different institutions in seven countries. The trend continued through the 1990s, as single-author papers became increasingly rare.<sup>1</sup>

None of this entirely solved the problem of fragmentation. Into the 21st century there remained entire communities of experts, for example water resource managers, who treated climate as something that fluctuated only within the unchanging boundaries described by historical statistics. In 2007 a group of applied meteorologists thought it necessary to explain to their peers that “30-yr normals are no longer generally useful.” News traveled slowly between disciplines. As late as 2020, when U.S. electric utilities were suffering disastrous climate-related failures, many utilities still based their planning on historical weather records rather than on future projections.

The more the research enterprise grew, the more scientists would need to specialize. Moreover, the imperatives of administration would always maintain boundaries between academic disciplines, and between the government agencies and organizations that supported them. However, by now everyone was keenly aware of the dangers of fragmentation and strove for better coordination. For many kinds of research, climatologists, geochemists, meteorologists, botanists, and so forth added to their disciplinary category a second form of identification—an all-embracing name reflecting a new social orientation and holistic approach—“environmental scientist.” They were borrowing the luster of a word that had come to stand for a widely admired attitude, with concerns embracing the Earth as a whole.<sup>2</sup>

Meanwhile, some scientists altered even their primary professional identification. By the end of the century the issue of climate change had become important and prestigious enough to stand on its own. Certain scientists who once might have called themselves, say, meteorologists or oceanographers, were now designated “climate scientists.” The terms “climate scientist” and “climate science” began to appear in books around 2000; around 2020 they passed “climatologist” and “climatology” in frequency. There was still no specific professional organization or other institutional framework to support “climate science” as an independent discipline. But that did not matter much in the new order of holistic interdisciplinary work.<sup>3</sup>

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<sup>1</sup> To be precise, 92 percent were single-authored pre-1940, and 58 percent during 1980-1988. Seven authors: e.g., Hansen et al. (1981); Dansgaard et al. (1982); 20 authors: Cess et al. (1989); multiple authorship in the 1990s is plain from scanning the references in IPCC (2001).

<sup>2</sup> Water resource managers: Milly et al. (2008); “no longer generally useful:” Livezey et al. (2007). U.S. utilities: Brad Plumer and Ivan Penn, “Climate Crisis Catches Power Companies Unprepared,” *New York Times* (July 20, 2021), online at <https://www.nytimes.com/2021/07/29/climate/electric-utilities-climate-change.html>. Doel (1997); Earth scientists had already begun to speak of “environmental sciences” as they coordinated Cold War research in the 1950s, Doel (2003).

<sup>3</sup> Designated “climate scientist:” e.g., Richard Lindzen, Testimony before the Senate Environment and Public Works Committee, May 2, 2001, available as appendix to United States Congress (107:1) (2001). Terms in books from Google Ngram viewer,

The internet helped bring people closer together. As soon as you heard about a paper in any journal on any subject, you could now find it online with ease, sometimes months before its formal publication. E-mail made it far easier to argue out ideas and exchange data, with as many people listening to the conversation as you liked. A few climate scientists went on to maintain blogs (for one, [realclimate.org](http://realclimate.org), founded in 2004 by nine researchers), encouraging a still more universal interchange. Meanwhile, as the importance of climate change became manifest, professional science writers in newspapers and magazines began to report on striking developments, alerting not only the public but scientists themselves to advances in the diverse fields of climate science.

(Of the papers in my bibliography for 1981-2000, *Nature* and *Science* tied with 25% each, including commentary and news articles, followed by the *J. Geophysical Research* with 15% and *Climatic Change* with 7%. *Tellus* fell below 1%. The journal *EOS: Transactions of the American Geophysical Union*, publishing a mixture of short scientific reviews and news articles, came in at 4%. A variety of new review journals titled *Advances in...* and *Reviews of...* collectively contributed another 4%. In my bibliography for 2001-2020, *Nature* published 16% of the total; this rises to a dominant 24% if we add the associated publications *Nature Geoscience*, *Nature Communications*, and especially *Nature Climate Change*, founded in 2007 as an online journal and converted to a regular journal in 2011. *Science* fell to 14%, but journals originating in the United States continued to add up to the largest share of papers, including *Geophysical Research Letters* at 7%, *Proceedings of the National Academy of Sciences* at 5%, *Eos* at 3% and *Climatic Change* and *Journal of Climate* at about 2.5% each. As another indicator, *Nature* and *Nature Climate Change* together published 11 of the 25 climate papers most cited by science journalists in the year 2020. A different picture appears if we look at essentially all papers of significant value no matter how specialized. Among the 13,500 items, mostly from 2010-2020, cited in the IPCC's comprehensive 2021 report, the *Nature* group again came first with some 12.5%, but closely followed by *Geophysical Research Letters* and *Journal of Climate* with 11.5% each and *Climate Dynamics*, a German journal founded in 1986, with 8%.<sup>1</sup>)

Still, the most important mechanism was the one that had sustained scientific communities for centuries: you went to meetings and talked with people. As one scientist described the system, "Most successful scientists develop networks of 'trusted' sources—people you know and get

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<https://books.google.com/ngrams/>. Note also, e.g., Utah State University offered a Bachelor of Science in Climate Science starting in 2017; the University of California at Berkeley Department of Earth and Planetary Science offered a minor in Climate Science starting in 2023.

<sup>1</sup> Cited by journalists: CarbonBrief.org, "Analysis: The climate papers most featured in the media in 2020," Jan. 13, 2021, online at <https://www.carbonbrief.org/analysis-the-climate-papers-most-featured-in-the-media-in-2020>. IPCC citations: S. Connors and F. Chavelli, "What 13,500 Citations Reveal about the IPCC's Climate Science Report," CarbonBrief.org, March 16, 2023, online at <https://www.carbonbrief.org/guest-post-what-13500-citations-reveal-about-the-ipccs-climate-science-report/>.

along with, but who are specialists in different areas... and who you can just call up and ask for the bottom line. They can point you directly to the key papers related to your question or give you the unofficial ‘buzz’ about some new high profile paper.”<sup>1</sup>

For climate scientists, the process of meetings and discussion went a long step farther when the world’s governments demanded a formal advisory procedure. The resulting Intergovernmental Panel on Climate Change (IPCC) was not really a single panel, but a nexus of uncounted international workshops, exchanges of draft reports, and arguments among individuals, all devoted to producing a single authoritative assessment roughly every half-dozen years. From the 1990s on the process engaged every significant climate scientist in the world (and many of the insignificant ones). At the time of its 2007 assessment, the IPCC process had grown to include 157 authors plus some 600 reviewers in the geophysical sciences, giving a rough idea of the size of the scientific community on which the world’s policy-makers now depended for crucial advice.<sup>2</sup>

In some fields the IPCC process became the central locus for arguments and conclusions. For example, in studying how atmospheric chemistry and aerosols affected climate, from the mid 1990s the main advances were consolidated in international workshops held under IPCC auspices. At the beginning of each six-year IPCC cycle, “scoping reports” were written to identify gaps in knowledge, deliberately influencing research program choices. At the end of a cycle an IPCC report would be acceptable only if it drew almost entirely on peer-reviewed articles, setting a deadline for publication which teams scrambled to meet.<sup>3</sup>

This process went farthest among computer modelers, whose efforts increasingly focused on cooperative projects to produce results designed and timed for the IPCC assessments. By the early 2000s a dozen major modeling groups and as many secondary ones were systematically, comparing results and arguing over the differences. Their models, now called “Earth System Models,” strove to incorporate virtually every known biological, chemical and physical process in land, sea, and air. So the enterprise as a whole served as a hub where experts from every climate-related specialty contributed ideas and data, interacting extensively with the modelers and one another.

The climate scientists felt intense pressure to come up with answers, as demanded by the world’s governments and by their own rising anxieties about the future. In countless informal exchanges and exhausting meetings, experts in each field hammered out agreements on precisely what they could, or could not, say with confidence about each scientific question. Their projections of

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<sup>1</sup> Gavin Schmidt, “AGU Hangover,” <http://www.realclimate.org/index.php?p=383>, posted Dec. 24, 2006.

<sup>2</sup> IPCC (2007b).

<sup>3</sup> Aerosols: Le Treut et al. (2007), p. 109. See Gavin Schmidt, “IPCC Special Report on 1.5°C,” Realclimate.org (Oct. 7, 2018), online at <http://www.realclimate.org/index.php/archives/2018/10/ipcc-special-report-on-1-5oc/>.

future climate, and the IPCC reports in general, were thus the output of a great engine of interdisciplinary research. This was a social mechanism for the creation of knowledge altogether unprecedented in its size, scope, complexity, and efficiency—and in its importance for the future of life on Earth.

By the 1990s climate scientists had established that their research deserved substantial support. The ratio of funding to needs, for a science whose practical consequences would not be seen for decades, approached the level of high-energy physics and cosmology, if not yet as generous as the totals for planetary space probes, biomedical research, and some other scientific and technical problems. Far from enjoying an easy ride, climate scientists warned there was an actual decline of observational networks in many parts of the world. Nobody knew exactly how much was being spent on climate research (a sign of the lack of international organization) but plausible estimates put it at three or four billion dollars a year at the end of the 1990s.

Since the mid 1980s the number of scientific papers published on climate change had been doubling and redoubling, from fewer than 100 in 1975 to about 7,000 per year in 2000—a hundred times the number in the mid-1970s (moreover, the number of pages per article and of words per page had risen sharply). About half of these papers originated in the United States. As a fraction of all scientific publications, papers on climate change doubled every five years from the 1980s into the early 2000s. The number of full-time climate researchers was likewise rising rapidly, reaching perhaps a thousand by the century's end. That might sound like a lot, yet it barely sufficed for a problem where the fate of entire populations would be swayed by dozens of different factors, each planetary in scope.<sup>1</sup>

## Maturity and Action (2001- )

During the 2010s the number of research papers related to climate change published each year climbed above 20,000. If you read *Science* or *Nature* you were more likely than not to find an item about climate change in any given week. The research enterprise was now so large and sprawling that specialty journals proved necessary; for example, from 2009 the American Geophysical Union and the European Geosciences Union each published its own peer-reviewed journal dedicated to descriptions of computer models and their uses. Around 2010 the rise in the number of research publications ceased to double every five years or so (exponentials cannot grow to infinity), but the linear rise continued to be steep.<sup>2</sup> Climate science was now mainstream,

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<sup>1</sup> Warnings: IPCC (2001a), p. 11. Stanhill (1999), see graph p. 396; Geerts (1999), pp. 639-40; Stanhill (2001), pp. 519-20.

<sup>2</sup> For context see Goodall (2008), p. 411, pdf online at <http://openaccess.city.ac.uk/12729/1/ClimateChangeJMI08.pdf>. *Geoscientific Model Development* (AGU, founded 2008), *Journal of Advances in Modeling Earth Systems* (EGS, founded 2009). Linear rise: eyeballing from figures by Rosamund Pearce in Robert McSweeney, "Analysis: the Most 'Cited' Climate Change Papers," CarbonBrief.org (July 8, 2015), online at <https://www.carbonbrief.org/analysis-the-most-cited-climate-change-papers>, in Minx et al.

with new developments covered thoroughly not only in science-oriented magazines like *New Scientist*, *Scientific American*, and *Discover* but in the popular press (which was increasingly read mainly online).

Around the start of the 21st century climate scientists forged a consensus that carried profound implications for economic policy and even modes of living. In 2001 the IPCC laboriously worked out a statement of the consensus: an unprecedented global warming, caused by humanity, was very likely underway and would get worse. Some 97% of the experts who published in the field agreed. (The prominent holdouts, lionized by right-wing media and politicians, were mostly stubborn old men with strong political convictions; by 2010 doubters had ceased publishing in peer-reviewed journals, bringing the professional consensus well above 99%.)

Governments and the public gave ever closer attention to the field, and its funding continued to be stronger than for many other scientific problems. That was not only because climate research addressed the anxiety that was growing among scientists and the public, but also because it required costly satellites, supercomputers, and expeditions by land and sea. The first decades of the century saw “a deluge of observations” of countless varieties. Traditionally geophysical data were jealously guarded until formal publication, but increasingly scientists opened their data banks to concerned citizens who demanded transparency, and to the many researchers outside elite circles who saw ways to contribute.<sup>1</sup>

The gravity of the issue sharpened political polarization, bringing severe pressures. Officials and the media demanded simple and immediate answers to complex questions. Worse, starting in the 1990s some politicians and many organizations and individuals not only questioned the validity of scientific theories and data, but smeared individual researchers and the entire climate science community as dishonest and corrupt. Studying climate change put researchers under stresses unknown in other fields of science. Prominent researchers faced vilification, hate mail, and outright death threats. Lawsuits fished for private communications in hopes of mining them for embarrassing snippets. It became necessary to create a Climate Science Legal Defense Fund. Most stressed of all were government scientists. They were constrained in what they could say, and anxious about their funding and even their jobs under right-wing administrations in Canada, Australia, and especially the United States during Donald Trump’s administration.

Increasingly since the 1980s climate scientists had worried about the world’s failure to take serious action against the ever more certain danger. “It keeps me awake at night sometimes,” one climate expert admitted, “thinking about my children or what will become of my state or my country, or my relatives, in the future.” By the late 2010s such feelings were spreading among the public at large, but climate scientists had to face the problem daily. Surveys found them burdened

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(2017), and in Callaghan et al. (2020).

<sup>1</sup> See footnote s.v. “97%” in the essay “The Carbon Dioxide Greenhouse Effect.” “Deluge:” Trevor F. Keenan, “The Terrestrial Carbon Sink and its Feedback to Climate,” in *Nature Climate Change* (2021).

to various degrees with anxiety, depression, grief at the losses to come, and sometimes anger at society's failure to rise to the challenge.<sup>1</sup>

Struggling to keep working with a positive attitude, some scientists tended, according to a survey, to “systematically avoid worst-case scenarios, even where they are as statistically likely to occur as not.” Already in 2007 the dean of global warming studies, James Hansen, had publicly warned against “scientific reticence,” the stance of avoiding any statements that might be criticized as “alarmist” or “sensational.” Scholars followed up with a study demonstrating how, at least in some areas, climate reports showed a tendency toward “erring on the side of least drama.” By 2020, however, even the staid IPCC was issuing unsparingly frightening warnings.

Worry in the community was turning to fear as the early predictions of danger proved accurate; the phrase “climate emergency” began to appear in the titles of many scientific articles. In a survey of the many authors of the 2021 IPCC report, nearly half of the respondents said that global warming had made them reconsider major life decisions, such as where to live and whether to have children. Some 20% reported “frequently” experiencing “anxiety, grief or other distress because of concerns over climate change.” Two-thirds of the respondents engaged in advocacy, from giving speeches to attending demonstrations. “For decades,” a trio of scientists told their colleagues in *Nature*, “scientists and policymakers have framed the climate-policy debate in a simple way: scientists analyse long-term goals, and policymakers pretend to honor them. Those days are over.”

With ever more climate scientists thinking that public communication was “integral to their job” (as some of them put it), from the 2010s a small academic field developed to study and advise them how to inform and persuade. Findings were promulgated, for example in a “Communications Handbook” the IPCC issued in 2018. Even the fraction of researchers who still wanted only to do research and publish scientific papers learned to watch out and prepare for ways the media might distort their findings. By the early 2020s, a substantial fraction of climate researchers had become so anxious and frustrated that they turned to activism, mobilizing in protests and civil disobedience actions (already in 2011 Hansen, ever a pioneer, had been arrested in a protest).<sup>2</sup>

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<sup>1</sup> Clayton (2018); “awake:” Andrea Dutton on Doug Hamilton et al., “Decoding the Weather Machine,” Nova/WGBH (2018); David Corn, “It’s the End of the World as They Know It,” Mother Jones (July 8, 2019), online at <https://www.motherjones.com/environment/2019/07/weight-of-the-world-climate-change-scientist-grief/>.

<sup>2</sup> Avoid: Head and Harada (2017); reticence: Hansen (2007); least drama: Brysse et al. (2013). IPCC authors survey (40% response): Tollefson (2021). “Climate emergency” in Web of Science titles: Shannon Osaka, “Why Many Scientists Are Now Saying Climate Change Is an All-out ‘Emergency’.” *Washington Post* (Oct. 30, 2023), online at <https://www.washingtonpost.com/climate-environment/2023/10/30/climate-emergency-scientists-declaration/>. “Days are over:” Xu et al. (2018), see Bob Berwyn, “This Was the Decade Climate



Meanwhile the community pressed on tirelessly with its research. Studies of how the climate system works were increasingly joined by studies relating more directly to technologies and policies. Particular attention went to predicting the future impacts of climate change and evaluating the impacts already evident. Working with experts in far-flung fields like wildfire history, epidemiology, city planning, or insurance underwriting brought the problem of disciplinary diversity to the highest level yet. Teams studying impacts had to struggle anew with the old problems of communication between disciplines—and scraping up funding from agencies whose parochial missions had no slots for the new problems. Adding to both the difficulties and the opportunities, international collaboration in this always global subject became still more ubiquitous in the new century. Climate science had expanded to touch almost any expert in anything. A comprehensive survey of scientists in *all* disciplines around the world reported that the overwhelming majority worried about climate change, and thought it called for “fundamental changes” in personal behavior and society.

A 2015 survey identified roughly 4,000 people who could be strictly described as members of the climate-science community; a third of them had been authors or reviewers of the most recent IPCC report. About a quarter of the respondents worked in the United States and Canada, with Germany second, the United Kingdom third, and fewer than 4% in any other country (although China was rising fast). Six-tenths worked in academia and most of the rest in non-academic publicly-funded research institutions. Nearly all of them were convinced that if too little was done to address climate change, the world faced a high “potential for catastrophe” within the next 50 years.<sup>1</sup>

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Scientists Stopped Being Polite,” Gizmodo.com (Dec. 31, 2019), online at <https://gizmodo.com/this-was-the-decade-climate-scientists-stopped-being-po-1840735992>. 2021. A discussion of scientist activism, with references: van Eck et al. (2024). “Integral:” Perga et al. (2024). For studies of public opinion, e.g., Leiserowitz, see footnotes in the essay on The Public and Climate Change-2. One pioneer in studying persuasion was John Cook, see his website [skepticalscience.com](http://skepticalscience.com); see also the [Links Page](#). Studies are reviewed by Moser (2009), Moser (2016). IPCC “Communications Handbook” online at <https://climateoutreach.org/reports/ipcc-communications-handbook/>. Watch out: Emily Atkin, “It’s Never Been Harder to Be a Climate Scientist,” *The New Republic* (July 27, 2017), online at <https://newrepublic.com/article/144056/its-never-harder-climate-scientist>. Civil disobedience: Grossman (2024).

<sup>1</sup> More practical studies: Fu and Waltman (2022); interdisciplinary work: Wadman (2024); rise of international collaboration in all geosciences: Ye et al. (2024); all scientists: Dablander et al. (2024). Climate-science community: Bray and von Storch (2016), pp. 4, 8-11, 108. Of the 100 most cited climate change papers published in the early 21<sup>st</sup> century, nearly 3/4 came from institutions in the US or UK, with most of the rest from Western Europe; among less-cited papers, contributions from China were getting a foothold: Robert McSweeney, “Analysis: The Most ‘Cited’ Climate Change Papers,” CarbonBrief.org (July 8, 2015), online at <https://www.carbonbrief.org/analysis-the-most-cited-climate-change-pa>

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