Rise of interdisciplinary research on climate

Spencer Weart[1]

Center for History of Physics, American Institute of Physics, College Park, MD 20740

Edited by Susan Solomon, Massachusetts Institute of Technology, Cambridge, MA, and approved June 11, 2012 (received for review May 24, 2011)

Until the middle of the 20th century, the discipline of climatology was a stagnant field preoccupied with regional statistics. 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 increasingly combined with physical science in hopes of understanding global climate dynamics. However, the dozen or so scientific disciplines that had something to say about climate were largely isolated from one another. In the 1960s and 1970s, worries about climate change helped to push the diverse fields into contact. Scientists interested in climate change kept their identification with different disciplines but 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.

history | global warming

At the middle of the 20th century, the professional study of climate was a scientific backwater (this article is based on my essay "Climatology as a profession," online at http://www.aip.org/history/climate/climogy.htm, which contains additional documentation and links to related material). 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. This information 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. This focus did not mean that climatologists overlooked unusual weather, because it was precisely the decade-long drought or extraordinary flood that most worried the farmer or civil engineer. However, 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 100-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-19th century, the discoveries of the Ice Ages and other great perturbations in the geological record raised questions about climate change on a global scale. The natural philosophers John Tyndall and James Croll, the physical chemist Svante Arrhenius, the geologist T. C. Chamberlin, the engineer G. S. Callendar, and others published innovative works. Given the broad range of their explanations, we could call these interdisciplinary contributions, although the term is anachronistic for most of the 19th century, because firm disciplinary boundaries were not established. In retrospect, this invaluable work laid the foundations for the present study of climate change. Many other scientists published speculations that are now justly forgotten. However, none of this information was of much interest to people engaged in the professional discipline of climatology as it stood in the mid-20th century: their concern was the climate of the present.

Typical was the situation at the US Weather Bureau, where an advisory group reported in 1953 that climatology was "exclusively a data collection and tabulation business" (ref. 1, p. 24). Not much money or administrative attention was committed to such work, and the intellectual prospects were not 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 (such studies continue to this day). Additionally, their tedious, painstaking style of scientific work would turn out to be indispensable for studies of climate change. However, scientists regarded the field (as one practitioner complained) as "the dullest branch of meteorology" (H. Lamb quoted in ref. 2, p. 90). 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" (ref. 3, p. 113).

When climatologists did try to go beyond statistics to explanations, they would explain the temperature and precipitation of a region in geographical terms: the sunlight at that particular latitude, the prevailing winds as modified by mountain ranges or ocean currents, and the like. The explanations were chiefly qualitative, with more hand-waving than equations. This information 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 science or geophysics (hardly any of the latter departments existed anyway). The geographical way of explaining regional climates was an essentially static exercise loosely based on elementary physics. The physics itself was 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, because meteorologists did not have an accurate picture of what they were trying to explain. Few measurements existed of the winds, 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

---

This paper results from the Arthur M. Sackler Colloquium of the National Academy of Sciences, "Fostering Advances in Interdisciplinary Climate Science," held March 31–April 2, 2011, at the AAAS Auditorium in Washington, DC. The complete program and audio files of most presentations are available on the NAS Web site at www.nasonline.org/climate-science.html.

Author contributions: S.W. wrote the paper.

The author declares no conflict of interest.

This article is a PNAS Direct Submission.

[1] E-mail: sweart1@gmail.com.

one scientist complained, “know little, and care less, about mathematics and physical science” (ref. 4, p. xii).

Climatology could hardly be scientific when meteorology itself was more art than science. If the general circulation of the atmosphere was a mystery, how could anyone calculate the course of storm systems? People had a variety of techniques for making crude weather forecasts. For example, whereas 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-h 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 PhD meteorologist, and indeed, most of the professionals in the US Weather Bureau 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” (5).

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. Based on fundamental physics, this work was by definition interdisciplinary. Through the first half of the 20th century, however, these efforts had little impact on most of the people whose careers were 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. Although 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” (ref. 6, p. 299). 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 of 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 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. However, 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 also 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 explanations 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 theory. 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 theory 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” (N. Shaw in ref. 7, p. 258). However, 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” (ref. 6, p. 4). 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 of 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 to 1950s)

However, 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. H. E. Landsberg’s 1941 textbook *Physical Climatology* (8) and the 1944 *Climatology* textbook written by two other meteorologists (9) showed how familiar physical principles underlay the general features of global climate and provided a rallying point for those individuals 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” (ref. 10, p. 277).

These textbooks came into use during the Second World War as meteorology professors trained thousands of meteorologists for the armed services. The training gave a big boost to the few universities where scientific meteorology already existed and led to additional 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 PhD 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. 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" (or at least, that is how some of them saw themselves) who broke away from the tradition of climatology as a mere handmaiden to forecasting (ref. 11, p. 31; ref. 12, chap. 9).

Leading the movement was 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 2 years at Vilhelm Bjerknes'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) (13). With their improved understanding of weather patterns, Bjerknes'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. Additionally, if the pattern of weather systems in a region changed, did that not 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 (14).

Rossby 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 meteorologists. The department trained some 1,700 in 1-year courses. Rossby also helped coordinate new programs for graduate training of meteorologists at several other American universities (15, 16).

Support continued after the war, as the Cold War and the expanding 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 (17). As Rossby (18) 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" (ref. 18, p. 16). Unlike the traditional regional climatologists, his group looked at the entire planet as a physical system.

War-trained young meteorologists also moved into the US 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" (19). 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" (ref. 1, p. 36). 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. Additionally, partly in response to the negative reports, conditions in the Bureau were improving rapidly. However, as for climatology at the Bureau, in 1957, another report described it as still nothing but a passive subsidiary to the main task of forecasting (20).

Stagnation was unacceptable to those individuals 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. Additionally, if nuclear bombs exploded, meteorology would be especially vital for tracking the deadly fallout. The Navy and Air Force, in particular, continued to use many hundreds of meteorologists. Also, in keeping with the new respect for science that they had learned during the war, the armed forces supported many 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 to 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 (21). An American Geophysical Union was also created in 1919 as an affiliate of the US 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 *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 (ref. 21, p. 286). 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. As for the scientific investigation of climate change, it appeared in a great variety of books and journals. I have investigated this work in a bibliography of over 2,000 items that I found significant for my study of the history of the science of climate change (22, 23). The only journals that stood out from the crowd in this period were *Quarterly Journal* and *Memoirs* of Britain's Royal Meteorological Society, which together, published 18% of the pre-1940 journal articles that I referenced in my work. The runner-up was *Journal of Geology*, with 9%.

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 US Air Force. Another big boost came in 1957–1958, 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 (24, 25). 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 *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 on climate change science. 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* (15%), *Journal of Meteorology* (10%), and *Quarterly Journal of the Royal Meteorological Society* (5%). *Journal of Geophysical Research* accounted for only 3%, about equal to *American Journal of Science* and *Journal of Geology*.]

Judging from a sample, about two-thirds of these papers were written in the United States—a much higher fraction than in earlier years. This finding was partly because the rest of the civilized world spent the 1950s recovering from the war's devastation. However, it was also because generous US government support for geophysical research, based on Second World War successes, did not falter, even when memories of the war faded. 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 of the sciences of the 20th century, expansion raised a risk of additional 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] Mandans," remarked J. A. Eddy, a solar physicist who took up climate studies in the 1970s (26). "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" (ref. 26, p. 4). 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 (27). 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 other 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. Also, theorists did not 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" (ref. 28, p. 200).

The gaps between fields of expertise went along with divergence in matters as fundamental as the sorts of data that people acquired and used. The economic importance of weather forecasting meant that climatologists could draw on a century-old and worldwide 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 (ref. 29, p. 623). 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" (ref. 30, p. 467).

Recognizing the problem, meteorologists made significant efforts to recruit students from various fields of the physical sciences and 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 the Department of the Geophysical Sciences. However, 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 meteorologists, very few worked on questions of long-term climate change (ref. 12, pp. 1–2).

Confronting Climate Change (1960s to 1970s)

For studies of climate, fragmentation was becoming intolerable by the 1960s. More than half of 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. Additionally, scholarly studies that extended the climate record far into the historical past were revealing large climate shifts. Most notable was evidence of a century or so of exceptional warmth in parts of medieval Europe and the North Atlantic. 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 50-year floods in each of the next 3 years (ref. 28, p.178). 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.

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" (ref. 31, p. vii). 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 database 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 (32). 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 30-y span became accepted as a baseline for predictions of future climates. However, experts increasingly saw that this practice, however necessary to provide answers to pressing questions, could be misleading. The first three decades of the century turned out to have weather 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.

The new thinking was displayed in full at a 1965 symposium held in Boulder, Colorado, on "Causes of Climate Change." Although the meeting made little special impression at the time, in retrospect, it was a landmark. 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. Lectures and roundtable discussions were full of spirited debate as rival theories clashed, and 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 J. M. Mitchell reported that our "comparatively amicable interlude" of warmth might give way to another Ice Age sooner than had been supposed (33). This foreboding possibility required scientists to understand the causes of climate change, he said, and suggest how we might use technology to intervene (ref. 33, pp. iii–iv and 157).

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 after the explosive growth of human population and industry. This view 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" (ref. 34, p. 76).

This view required a new kind of research community, more closely linked to other fields and other kinds of science. This need was happening in all of 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 individuals who did attack 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). However, 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. On top of these external influences, it seemed 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" (ref. 35, p. 178).

The shortcomings of the old single-cause approach were especially visible to those individuals 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, and academic scientists with their theories and equations—to communicate with one another in a common enterprise and, beyond communication, talk with other scientists of every stripe.

Means of Communication (1970s to 1980s)

The changes in meteorology and geophysics were typical of a movement in all of 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. This 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 discussion was timely, because 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.

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, computer scientists, or paleobotanists. Not many would identify themselves as primarily a climate change scientist. There was not even an accepted term to describe the nondiscipline. 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 more broadly defined fields, such as atmospheric sciences, in which climate change was included only as one among many elements.

In 1977, one landmark for the recognition and coalescence of a scientific discipline did come with the foundation of a dedicated journal, *Climatic Change*. However, unlike many new journals, this journal 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 (36). The founding editor, S. H. 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 (37). Many scientists believed that solid research could be done only within the strict framework of a traditional discipline (ref. 37, pp. 75–76).

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*. However, 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, *Journal of the Atmospheric Sciences* published 10% of all papers, and *Quaternary Research* published 7.5%. *Science* published 23% (if one includes a few news articles), and *Nature* published 10%. *Tellus* was down to 5%, equal to *Journal of Geophysical Research*, followed by *Journal of Applied Meteorology* at 4%. *Quarterly Journal of the Royal Meteorological Society* fell to 2.5%.

To a degree, climate science remained "a scientific backwater," as one of its leading figures recalled decades later (38). "There is little question," he claimed, "that the best science students traditionally went into physics, math and, more recently, computer science" (38). The study of climate was not a field where you could win a Nobel Prize or a lucrative patent. You were not likely to win great public fame or get 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, and they took 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. Although 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 the National Aeronautics and Space Administration, 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" (39). 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 approach was fundamentally novel. Many things contributed to the 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 (40).

For studying a system with features dispersed among many specialties, the solution was collaboration. This trend was strong in all of the sciences, because research problems spanned ever more complexities. Scientists with different types of expertise exchanged ideas and data or worked 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, and 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 papers connected with climate change. Both of 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. Of the papers in my bibliography for 1981–2000, *Nature* and *Science* tied with 25% each, including commentary and news articles, followed by *Journal of 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%.

Climate science was now mainstream, with new developments covered thoroughly not only in *Science* and *Nature* but the popular press and in the 2000s, on the internet. The number of scientific papers in the field soared exponentially: as a fraction of all scientific publications, papers on climate change doubled every 5 years from the 1980s into the 2000s (41).

An especially powerful mechanism for cooperation was the formation of projects to address particular interdisciplinary topics. For example, 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. COHMAP 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 of the collaborators would convene from time to time in large assemblies. However, a few leaders would also gather in smaller meetings, "often hosted in home settings where conversations were unhurried and brainstorming was lively" (ref. 42, p. 107). Computer models confronted paleontological data in a continual dialogue, each discrepancy forcing one side, 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 y ago.)

COHMAP was only one example of many 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.

Cooperation and Integration (1990s to 2000s)

Projects with multiple contributors were becoming common in all of 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 carbon dioxide—were a vanishing breed. Nearly all of the papers written before 1940 in my bibliography were published under a single name; only a few were the work of two authors. However, of papers written in the 1980s, less than one-half had one author. Many of the rest had more than two authors, and a paper listing, say, seven authors was no longer extraordinary. Large projects were represented by, for example, a 1989 paper with 20 authors from 13 different institutions in seven countries (43). The trend continued through the 1990s, and single author papers became increasingly rare.

None of this cooperation entirely solved the problem of fragmentation. Into the 21st century, there remained entire communities of experts (for example, water resource managers) who still treated climate as something that fluctuated only within the unchanging boundaries described by historical statistics (44). Additionally, 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 (15, 24).

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 (38). There was still no specific professional organization or other institutional framework to support climate science as an independent discipline. However, this lack of independence did not matter much in the new order of holistic interdisciplinary work.

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 (notably realclimate.org), encouraging a still more universal interchange.

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 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" (45).

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 6 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 measure of the size of the scientific community on which the world's policymakers now depended for crucial advice (46).

In some fields, the IPCC process became the central locus for arguments and conclusions. This process went farthest among computer modelers, whose efforts increasingly focused on cooperative projects to produce results for the IPCC assessments. When climate modelers studied the details of each factor that went into their calculations and sought large sets of data to check the validity of their results, they had to interact with every specialty that had anything to say about climate change. Every group felt an intense pressure to come up with answers, which were demanded by the world's governments and their own rising anxieties about the future. In countless grueling exchanges of ideas and data, the 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 future climate and the IPCC reports in general were, thus, the output of a great engine of interdisciplinary research. In the world of science, this social mechanism was altogether unprecedented in its size, scope, complexity, and efficiency—as well as its importance for future policy.

1. United States Department of Commerce, Advisory Committee on Weather Services (1953) *Weather is the Nation's Business* (US Govternment Printing Office, Washington, DC).
2. Alexander T (1974) Ominous changes in the world's weather. *Fortune* 89:90–95, 142–152.
3. Eady ET (1957) Climate. *The Earth and its Atmosphere*, ed Bates DR (Basic Books, New York), pp 113–129.
4. Stringer ET (1972) *Foundations of Climatology* (Freeman, San Francisco).
5. Platzman G (1950) *Letter to Charney J, 18 June, Box 14:451, Charney Papers* (MIT Archives, Cambridge, MA).
6. Lamb HH (1959) Our changing climate, past and present. *Weather* 14:299–318; reprinted in Lamb HH (1966) *The Changing Climate: Selected Papers* (Methuen, London), pp 291–220.
7. Harmer FW (1925) Further remark on the meteorological conditions of the Pleistocene Epoch. *Q J R Astron Soc* 51:247–259.
8. Landsberg HE (1941) *Physical Climatology* (Pennsylvania State College, State College, PA).

9. Haurwitz B, Austin JM (1944) *Climatology* (McGraw-Hill, New York).
10. Sutcliffe RC (1963) Theories of recent changes of climate. *Changes of Climate. Proceedings of the Rome Symposium Organized by UNESCO and the World Meteorological Organization, 1961 (UNESCO Arid Zone Research Series, 20)* (United Nations Educational, Scientific and Cultural Organization, Paris), pp 277–280.
11. Smagorinsky J (1991) *Climate's Scientific Maturity. Climate in Human Perspective: A Tribute to Helmut F. Landsberg*, eds Baer F, Canfield NL, Mitchell JM (Kluwer, Dordrecht, The Netherlands).
12. Nebeker F (1995) *Calculating the Weather: Meteorology in the 20th Century* (Academic, New York).
13. Friedman RM (1989) *Appropriating the Weather: Vilhelm Bjerknes and the Construction of a Modern Meteorology* (Cornell Univ Press, Ithaca, NY).
14. Heymann M (2010) The evolution of climate ideas and knowledge. *Wiley Interdiscip Rev Clim Change* 1:581–597.
15. Doel R (2003) Constituting the postwar Earth sciences: The military's influence on the environmental sciences in America after 1945. *Soc Stud Sci* 33:635–666.
16. Byers HR (1959) Carl-Gustaf Rossby, the organizer. *The Atmosphere and the Sea in Motion*, ed Bolin B (Rockefeller Institute Press, New York), pp 56–59.
17. Harper KC (2006) Meteorology's struggle for professional recognition in the USA (1900–1950). *Ann Sci* 63:179–199.
18. Rossby C-G (1959) Current problems in meteorology. *The Atmosphere and the Sea in Motion*, ed Bolin B (Rockefeller Institute Press, New York), pp 9–50.
19. Spilhaus A (1989) *Interview by Doel R* (Niels Bohr Library & Archives, American Institute of Physics, College Park, MD).
20. National Academy of Sciences, Division of Earth Sciences, Committee on Climatology (1957) *First General Report on Climatology to the Chief of the Weather Bureau* (National Academy of Sciences, Washington, DC).
21. Good GA (2000) The assembly of geophysics: Scientific disciplines as frameworks of consensus. *Stud Hist Philos Modern Phys* 31B:259–292.
22. Weart SR (2008) *The Discovery of Global Warming* (Harvard Univ Press, Cambridge, MA), 2nd Ed.
23. Weart SR (2002) *Bibliography.* Available at http://www.aip.org/history/climate/bib.htm. Accessed January 10, 2012.
24. Doel R (1997) The earth sciences and geophysics. *Science in the Twentieth Century*, eds Krige J, Pestre D (Harwood, London), pp 361–388.
25. Doel RE (1998) Geophysics in universities. *Sciences of the Earth. An Encyclopedia of Events, People, and Phenomena*, ed Good GA (Garland, New York), Vol 1, pp 380–384.
26. Eddy JA (1999) *Interview by Weart S* (Niels Bohr Library & Archives, American Institute of Physics, College Park, MD).
27. Shackleton NJ (2003) Shackleton receives 2002 Maurice Ewing medal. *Eos Trans AGU* 84:72.
28. Lamb HH (1997) *Through All the Changing Scenes of Life: A Meteorologist's Tale* (Taverner, Norfolk, UK).
29. Charnock H (1998) Ocean-atmosphere interactions. *Sciences of the Earth. An Encyclopedia of Events, People, and Phenomena*, ed Good GA (Garland, New York), Vol 2, pp 623–625.
30. Wallén CC (1963) Aims and methods in studies of climatic fluctuations. *Changes of Climate. Proceedings of the Rome Symposium Organized by UNESCO and the World Meteorological Organization, 1961 (UNESCO Arid Zone Research Series, 20)* (United Nations Educational, Scientific and Cultural Organization, Paris), pp 467–473.
31. Rumney GR (1968) *Climatology and the World's Climate* (Macmillan, London).
32. Cressman GP (1996) The origin and rise of numerical weather prediction. *Historical Essays on Meteorology 1919–1995*, ed Fleming JR (American Meteorological Society, Boston), pp 21–39.
33. Mitchell JM, Jr., ed (1968) Causes of climatic change. *Meteor Mon* 8(30).
34. Barrett EW, Landsberg HE (1975) Inadvertent weather and climate modification. *CRC Crit Rev Environ Control* 6:15–90.
35. Lamb HH (1969) Climatic fluctuations. *General Climatology, World Survey of Climatology*, ed Flohn H (Elsevier, Amsterdam), Vol 2, pp 173–247.
36. Schneider SH (1991) Editorial. *Clim Change* 19:v–vi.
37. Schneider SH (2009) *Science as a Contact Sport. Inside the Battle to Save the Earth's Climate* (National Geographic, Washington, DC).
38. Lindzen R (2001) *Testimony Before the Senate Environment and Public Works Committee, May 2, 2001, Appendix to US Congress (107:1), Senate, Committee on Governmental Affairs, The Climate Change Strategy and Technology Innovation Act of 2001: Hearings* (US Government Printing Office, Washington, DC).
39. Conway EM (2008) *Atmospheric Science at NASA: A History* (Johns Hopkins Univ Press, Baltimore).
40. Edwards PN (2010) *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming* (MIT Press, Cambridge, MA).
41. Goodall AH (2008) Why have the leading journals in management (and other social sciences) failed to respond to climate change? *J Manage Inq* 17:408–420.
42. Webb T (2007) COHMAP: Origins, development, and key results. *Climate Variability and Changes: Past, Present and Future. John E. Kutzbach Symposium*, ed Kutzbach G (Center for Climatic Research, University of Wisconsin-Madison, Madison, WI), pp 105–117.
43. Cess RD, et al. (1989) Interpretation of cloud-climate feedback as produced by 14 atmospheric general circulation models. *Science* 245:513–516.
44. Milly PCD, et al. (2008) Climate change. Stationarity is dead: Whither water management? *Science* 319:573–574.
45. Schmidt G (2006) *AGU Hangover*. Available at http://www.realclimate.org/index.php?p=383. Accessed December 24, 2006.
46. Intergovernmental Panel on Climate Change (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC* (Cambridge Univ Press, Cambridge, UK).