Weather and Climate as Shape-Shifting Nouns: Gordian Knots of Understanding and Prevision

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> "[Technology] is cutting the Gordian Knot instead of untying it"
> — Carl-Gustaf Rossby[1]

> "Why should nearly perfect forecasts be unattainable?" — Chaos"
> — Edward N. Lorenz[2]

"Climate" deserves to be a keyword in the vocabulary of culture and society. It is arguably one of the most linguistically complicated words — a historically shape-shifting noun — whose meaning has changed and is changing, perhaps faster than the climate itself. Its nature, history, and vicissitudes are key concepts organizing our ideas of the aerial environment and our relationship to it.[3] Although climate can be depicted and modeled, it cannot be directly visualized or forecast. The relationships of climate to meteorology and meteorology to climate studies are also dynamic. This article reviews the changing nature of ideas about climate over an extended time period, with special focus on developments in dynamic meteorology and dynamic climatology in the period 1900-1960, and with an update for the twenty-first century based on the implications of chaos theory. It adds a temporal dimension to the science and philosophy of weather prediction and climate change and the ways we think about the interrelationships of weather and climate.

It may be a truism for historians that anything that can be named had different meanings in different eras, but some philosophers, with notable exceptions, have overlooked this.[4] When doing epistemology, it is important to think about the history of

[1] C.-G. Rossby, "Current Problems in Meteorology," *The Atmosphere and the Sea in Motion: Scientific Contributions to the Rossby Memorial Volume*, Bert Bolin, ed. (Stockholm: Rockefeller Institute Press and Oxford University Press, 1959), 9-50, quoted on 36.

[2] Undated lecture transparency in the Papers of Edward N. Lorenz, U.S Library of Congress, Manuscript Division.

[3] J.R. Fleming, "Climate, Change, History," *Environment and History* 20 (2014): 577-586.

[4] Nietzsche and Whitehead are notable exceptions; see "epistemology" in the *Internet Encyclopedia of Philosophy*, http://www.iep.utm.edu/epistemo/

the objects under discussion and how the meaning of terms has changed. As Mike Hulme has written recently, "Like all powerful ideas, climate change can be deceptively simple to define and yet subject to a multiplicity of cultural meanings and technical interpretations." It is important to clarify the historical context and to think about what we are thinking about when we use terms such as climate, climate change, meteorology, dynamics, and models.[5]

Apprehension and Authority

In *Historical Perspectives on Climate Change* (1998), I examined climate and climatic changes from the Enlightenment to the late-twentieth century, asking the following questions, among others: "How do people (scientists included) gain awareness and understanding of phenomena that cover the entire globe, and that are constantly changing on time scales ranging from geological eras and centuries to decades, years, and seasons?" "How was this accomplished by individuals immersed in and surrounded by the phenomena?" and, "How were privileged positions created and defined?"[6] Since atmospheric scientists lack the ability to observe the climate system in its entirety (as an astronomer might view a star or planet) or to experiment on it directly (as a chemist might view a reaction), the pathways to the many and varied scientific understandings of climate are not at all straightforward; vexed too are the interrelations between elite and popular perceptions of the environment.

There are three major definitions of the term apprehension that can be applied to climate: (1) awareness and understanding, (2) anticipation and dread, (3) intervention and control. Climate is an elusive entity. It is more than the average condition of the atmosphere compiled from weather statistics; it is something much more fundamental than that: it is lived experience providing frameworks for the material possibilities of life, inseparable from the temporality and specificity of the social world. Collectively, climate shapes life in specific places in fundamental and dramatic ways; it is woven into the fabric of the human past and future; both the experience and knowledge of climate is shaped by and enframed in our lifestyles, our seasonality, our clothing and housing, our aspirations and our tragedies. Climate involves themes of dominant empires, colonial pride and pioneer mentalities; popular, religious and racial sentiments; imposed and imported ideologies; and resilience to extreme conditions of flood and drought as embodied in agricultural and technological practices. Climate is both intimate and universal, involving local experiences of global change.[7] Its influences are as proximate,

[5] Mike Hulme, "Climate Change (concept of)," *International Encyclopedia of Geography* editor-in-chief Douglas Richardson (Hoboken, NJ: Wiley-Blackwell/Association of American Geographers, 2015). J.R. Fleming, "Historical Perspectives on Shape-shifting Nouns: Climate, dynamics, models." Invited talk for *Models and Knowledge in Climate Sciences: Historical, Scientific and Philosophical Perspectives*, Rotman Institute of Philosophy Annual Conference, London, Ontario, Canada, Oct. 2014, http://www.rotman.uwo.ca/new-video-posted-james-fleming-dynamic-climatology-historical-perspectives-on-shape-shifting-nouns

[6] J.R. Fleming, *Historical Perspectives on Climate Change* (New York: Oxford University Press, 1998, 2005).

[7] *Intimate Universality: Local and Global Themes in the History of Weather and Climate*, James Rodger Fleming, Vladimir Jankovic, and Deborah R. Coen, eds. (Sagamore Beach, MA: Science History

and personal, as a breath of fresh air, a drink of local water, or an attachment to place. Its vicissitudes are increasingly associated with collectively held apprehensions (fears really) of the destructive reach of global civilization on the planet.[8]

How then were privileged positions on such an elusive entity established? One approach, popular in the eighteenth century, was through appeals to authority—references to culture, to historical literature, to first impressions of explorers, or to the memory of the elderly [See Fenby, this volume]. This was the rhetorical strategy of Enlightenment and early-American writers who wanted to support a particular theory of cultural development or decline. In *Réflexions critiques sur la poësie et sur la peinture* (1719), Abbé Du Bos examined the causes of the rise and fall of the so-called illustrious ages in the arts and sciences, attributing them primarily to changes in *les causes physiques* (the nature of the air, land, soil and especially climate). Many Enlightenment era authors followed this lead, including the Baron Montesquieu and Thomas Jefferson, who attributed climatic change in Europe and America to human settlement, including forest clearing, marsh drainage and cultivation.[9]

Also in vogue was the practice of collecting massive amounts of meteorological data over large areas and extended time periods in the hope of deducing climatic patterns and changes [See Munger, this volume]. Individual observers in particular locales dutifully tended to their journals, and networks of cooperative observers gradually extended the meteorological frontiers. Beginning in earnest in the nineteenth century, scientists tabulated, charted, mapped, and analyzed observations to provide climatic inscriptions. This process profoundly changed climate discourse and established the foundations of the science of climatology. Climates were seen as stable, to be described by geographers and studied by statisticians. The noted Austrian climatologist Julius Hann wrote in 1897 that climate is "the sum total of the meteorological phenomena that characterize the average condition of the atmosphere at any one place on the earth's surface."[10] This became the dominant working definition, still invoked today.

A third approach to privileged knowledge was to establish from first principles what the climate ought to be and how it ought to change. Approaches drawn from physical, mathematical, geological, and astronomical evidence and principles tended to be most satisfying to those scientists working within a particular disciplinary perspective. Most scientists had one favorite causal mechanism and only grudgingly admitted other possible secondary causes of climate change [See articles by Ellingsen and Lehmann, this volume]. In the mid-twentieth century Tor Bergeron, an acolyte of the Bergen school of meteorology, defined a "dynamic climatology," which supplemented statistical means with detailed explanations of air masses, fronts and other thermodynamic factors influencing the climate. According to Bergeron, climatology had been essentially the systematic compiling of statistics on the individual meteorological elements, without an organized attempt to get at the underlying dynamic or thermodynamic phenomena in their entirety. Since descriptive climatology offered no unifying picture of the prime

Publications/USA, 2006); *Osiris* 26, *Klima.* James Rodger Fleming and Vladimir Jankovic, eds. (Chicago: University of Chicago Press, 2011).

[8] Naomi Oreskes and Erik M. Conway, *The Collapse of Western Civilization: A View from the Future* (New York: Columbia University Press, 2014).

[9] Fleming, *Historical Perspectives.*

[10] Julius Hann, *Handbook of Climatology*, trans. R. deC. Ward (New York: 1903), 1.

thermodynamic forces controlling the climate, Bergeron applied concepts of air masses and fronts to outline a comprehensive dynamic climatology explaining how the several complete thermodynamic units, rather than the unrelated distribution of the individual meteorological elements, control the climate of a region. An older, static climatology may say how much it rained in a given year; dynamic climatology would say when, where, and why it rained.[11]

Another approach to privileged climate knowledge has been through technology. In part with the invention and standardization of meteorological instruments and the networking of meteorological observers, but more recently in the explosive growth of transformative technologies of communication and aerospace in the twentieth century, weather and climate observations have been rendered both global and three dimensional. A number of transformative technologies — including radar, nuclear tracers, digital computers, sounding rockets, and weather satellites — fostered the emergence of the interdisciplinary atmospheric sciences after World War II. Scientists working with computers in meteorology at the time demeaned the older, descriptive and statistical forms of geography as hardly constituting a physical science. Today many scientists working at the interface of remote sensing and modeling are hoping, through advances in technology, to provide new privileged positions. For most scientists the goal is better understanding of climate; for some it is also prediction and control.

Lest we overlook the applied dimensions, in the 1960s, climatologist Helmut Landsberg described what he called “techno-climatology” as comprising the influences of climate on the infrastructure of modern life, both in the quotidian sense, but also in the applicability of climatic information to engineering and city planning and the effects of climate on commerce and industry [See articles by Janković and Vollset, this volume]. .[12] By including industry, Landsberg raised the possibility of combining the history of natural and artificial environments, through case studies of climate, climate modification, and climate control as it affects storage, warehousing and the efficiency, health, and safety of workers.

Climate is bigger than any single journal, book or even disciplinary approach. Its history draws in part on the histories of particular sciences such as astronomy, chemistry, computer science, geography, geology, meteorology, paleontology, and physics; and in part from much broader historical currents. Historians with particular disciplinary interests have examined all of these fields before, at least to some extent. With global climatic change as the new focus, however, a new interdisciplinary picture begins to emerge that includes both elite and popular apprehensions. Coming full circle, modelers increasingly are appealing to the authority and consensus being generated by the Intergovernmental Panel on Climate Change (IPCC). In reality, however, climatologists sense that they have lost control of a subject they never fully mastered: the grand global narrative of scientific rationality wedded to human behavior, technological solutions, and policy innovations. New voices, untrained in the nuances of the atmospheric sciences, from the press, the public, the state, the environmental movement, have flooded the literature, adding polarizing voices, while venerable but vulnerable practices of peer review and journal publication have taken back seats to the new electronically facilitated

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[11] Tor Bergeron, "Richtlinien einer dynamischen Klimatologie,” *Meteorologische Zeitschrift* 47 (1930): 246-262.

[12] Helmut Landsberg, *Physical Climatology*, 2nd ed. (Du Bois, Penna.: Gray, 1964), 389.

'peer-to-peer' review and ubiquitous blogs, tweets and quacks. Just as the world turns to crucial questions of what is to be done, it appears certain that the climatologists have lost voice, ownership, authority, status – and in many cases their innocence, patience and even their tempers, while others, ever more strident, speak for them, ever more shrilly. Skeptics (a venerable position in philosophy and science) hold that we do not know as much as we think we do about climate, especially regarding the sensitivity of the climate to carbon dioxide, while so-called "deniers" (a form of name-calling), maintain that we should do nothing about climate change. Climate interventionists, on the other hand, propose to control weather systems and 'fix' the climate with heavy-handed technologies: seed the clouds to create or dissipate rain on demand, launch a fleet of space mirrors, pump sulfates into the stratosphere to cool the planet, capture the world's carbon emissions and sequester them safely and economically for thousands of years. As the climate changes ever so slightly (perhaps more next decade according to the IPCC?), economies stumble and mitigation plans move ahead haltingly, if at all. The current consensus on global climate change calls into question the trajectory of modern civilization: Will it empower or perhaps overthrow the status quo? Or are climate and climate change shape-shifting nouns? Such ideas might sound like science fiction, but in fact they are part of a very old story rooted in human apprehensions and aspirations to control nature.[13]

Models

Models too are shape-shifting nouns. Consider the ancient explanation of the solidness of a material proposed by the Greek philosopher Democritus: "The solidness of a material corresponds to the shape of the atoms involved. Water atoms are smooth and slippery; salt atoms are sharp and pointed; air atoms are light and whirling." According to the epistemology of shape-shifting nouns, "We, in actuality, grasp nothing for certain."[14]

A digital computer is, in reality, just a really big and fast calculating machine, not a "model" itself, but a useful tool. In the late 1940s C.-G. Rossby, Jule Charney and their associates articulated the simplified differential equations of upper atmospheric flow and expressed them as finite difference equations suitable for machine calculation. This involved replacing the time and space derivatives with differences of finite magnitude, for example, one-hour time increments and 300-kilometer horizontal grid spacing. The meteorological problem then consisted of programing the computer to compute the change of the state of the atmosphere, hour after hour, in the system so defined. With a computer fast enough to complete these calculations in less than one hour, the expected changes can be added to the originally observed values to generate, via an iterative or "bootstrapping method," a 12- or 24-hour or longer prognosis. This was in fact the method used in routine numerical weather prediction services, available, at least for the upper atmosphere, since 1954 in the United States and, to a limited extent, in Sweden. The next logical and tractable step at the time consisted in integrating the atmospheric equations for a dynamic, moist, heated atmosphere forever — the so-called "infinite

[13] J.R. Fleming, *Fixing the Sky: The checkered history of weather and climate control* (New York: Columbia University Press, 2010).

14 Jerry Coffey, "Democritus Atom," Universe Today, http://www.universetoday.com/60058/democritus-atom

forecast" — proposed by John von Neumann, Jule Charney, and Harry Wexler — and first attempted by Norman Phillips. The result was not a forecast or a prediction of particular weather conditions, but a limiting case converging on the statistical features of the general circulation, independently of whatever initial conditions may have existed. This is not a forecast in the usual sense, but a model test. Modern climate models, with secularly changing boundary conditions, are distant (very distant) cousins of this process.

Some may wonder how weather and climate are interrelated rather than distinct. Both, for example, are at the center of the debate over greenhouse warming and hurricane intensity. A few may claim that rainmaking, for example, has nothing to do with climate engineering, but any intervention in the Earth's radiation or heat budget (such as managing solar radiation) would affect the general circulation and thus the location of upper-level patterns, including the jet stream and storm tracks. Thus the weather itself would be changed by such manipulation. Conversely, intervening in severe storms by changing their intensity or their tracks, or modifying weather on a scale as large as a region, a continent, or the Pacific basin would obviously affect cloudiness, temperature, and precipitation patterns, with major consequences for monsoonal flows and ultimately the general circulation. If repeated systematically, such interventions would influence the overall heat budget and the climate. In such a perturbation analysis, weather and climate are distinctly interrelated.

The Gordian Knot

Atmospheric researchers have long attempted to untie the Gordian Knot of meteorology — that intractable and intertwined tangle of observational imprecision, theoretical uncertainties, and non-linear influences — that, if unravelled, would provide perfect prevision of the weather for ten days, of seasonal conditions for the next year, and of climatic conditions for a decade, a century, a millennium, or longer. In the first six decades of the twentieth century, from the dawn of applied fluid dynamics to the emergence of the interdisciplinary atmospheric sciences, three interconnected generations of scientists aimed to extend and improve atmospheric measurements and to predict the future state of the atmosphere. In the first decade of the twentieth century, researchers pinned their hopes on wireless telegraphy and the dawning of the aerial age. Several decades later, radio, aviation, rockets, digital computing, and Earth-orbiting satellites had opened up entirely new research horizons. Each generation of atmospheric researchers aspired to a more global meteorology, zealously incorporating capabilities provided by new technologies into their science as they worked to link theory with practice. Each generation experienced, in their own ways, the heady feeling that they were the direct beneficiaries of new technological breakthroughs and that they stood on the brink of a major revolution in the science and practice of meteorology. Their goal was to produce accurate information about the state of the entire atmosphere, complete mathematical portrayals of its varied and changing states, and useful and timely forecasts of its near- and long-term future. Their soaring aspirations faced a multiplicity of crushing practical limitations exacerbated by war, bureaucracy, economic downturns, prejudice, and technological limitations.[15]

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[15] J.R. Fleming, *Inventing Atmospheric Science* (Cambridge, Mass.: MIT Press, 2016).

In 1895 Cleveland Abbe, éminence grise of American meteorologists and editor and translator of several volumes of geophysical papers, pointed out that meteorology needed a deductive treatise on the laws governing the atmosphere as complete and rigorous as the *Celestial Mechanics* of Laplace:

> Meteorologists can never be satisfied until they have a deeper insight into the mechanics of the atmosphere. Something more is needed than the most perfect organization for observing, reporting and publishing the latest news from the atmosphere. It is not enough to know what the conditions have been and are, but we must know what they will be, and why so. We must have a deductive treatise on the laws governing the atmosphere as complete and rigorous as the "Celestial Mechanics"º of LaPlace, and this will necessarily be a treatise on the application to the atmosphere of the general laws of force, or what is technically known as the dynamics and thermo-dynamics of gases and vapors.[16]

Note that Abbe did not differentiate between weather and climate, but emphasized the laws governing the entire atmosphere.

Less than a decade later, Vilhelm Bjerknes (1862-1951) initiated a neo-Laplacian program to measure current atmospheric conditions and to calculate the future state of the weather using the equations of hydrodynamics and thermodynamics. He said this in 1902 in the *Meteorologische Zeitschrift*: "Each task of theoretical mechanics is, when it is placed in direct form, a prognostic, just like the most well-known task of practical meteorology. The goal is to predict the dynamic and physical condition of the atmosphere at a later time, if at an earlier given time, this condition is well known."[17] According to Bjerknes, the central problem of the science of meteorology is weather prediction by rational dynamical-physical methods. He wanted to place meteorology on solid observational and theoretical foundations. In 1904, he published "Weather forecasting as a problem in mechanics and physics." [18] Here he stated the problem of weather forecasting as an initial-value problem in mathematics involving the ideal gas law, the first law of thermodynamics, the conservation of mass, and the dynamical equations of an ideal compressible gas. He wrote that the necessary and sufficient conditions for a rational solution of the problem of meteorological prediction include a *sufficiently* accurate knowledge of the state of the atmosphere at a certain time and a *sufficiently* accurate knowledge of the laws according to which one state of the atmosphere develops from another. These statements bring together massive programs in observation, theory, and forecasting and are really philosophical statements of faith in rational mechanics, raising the fundamental question of how far we can see into the future. Starting from a detailed, if not perfect, set of atmospheric measurements, it should be possible to take a finite, if not perfect, step forward using the time-dependent equations of atmospheric motion. This was the first step, for Bjerknes, in unraveling the Gordian Knot of meteorology. Bjerknes's use of the word *sufficiently* in these statements tempered his determinism. The term undoubtedly derives from his personal experience in trying to measure, with any precision, the initial state of the atmosphere over an extended area and

[16] Cleveland Abbe, "The Needs of Meteorology," *Science* n.s. 1, no. 7 (1895), 181-182.
[17] Vilhelm Bjerknes, "Cirkulation relativ zu der Erde," *Meteorologische Zeitschrift* 19 (1902): 97-108, on 108.
[18] Vilhelm Bjerknes. "Das Problem der Wettervorhersage, betrachtet vom Standpunkte der Mechanik und der Physik," *Meteorologische Zeitschrift* 21 (1904): 1-7.

from his exposure to the mathematical lectures of Henri Poincaré in Paris. At the time, Poincaré (1854-1912) was writing his three-volume *Les méthodes nouvelles de la mécanique celeste* in which he employed analogies with fluid flow to characterize all motions of mechanical systems. In his essay *Science et méthod*, Poincaré raised the issue of a computation's sensitivity to initial conditions and undermined the notion of a perfectly precise observation of nature, noting that, "small differences in the initial conditions produce very great ones in the final phenomena." This is now recognized as one of the canons of chaos theory.[19]

Bjerknes insisted on the necessity of taking measurements in the centimetre-gram-second (c.g.s.) system and worked to rationalize the analysis of observations. He accepted a call to Leipzig in 1913 to establish a geophysical institute. This gave him access to a dense network of upper-air observations. The tragedy and hardships of World War I made conditions insufferable in Germany, and in 1917 Bjerknes moved to Bergen, Norway with his family where his group established a network of stations sufficiently dense to identify cold fronts and warm fronts as components of an ideal wave cyclone model. Because exact solutions to his system of atmospheric equations were impossible, Bjerknes promoted the use of graphical methods including streamline analysis. He founded the Bergen school of meteorology in 1919, where graphical methods prevailed. Working in concert with his many associates, and with regular funding from the Carnegie Institution, the Bergen school delineated the properties of air masses and described the life history of cyclones developing along the polar front. Bjerknes once remarked, "During 50 years meteorologists all over the world had looked at weather maps without discovering their most important features. I only gave the right kind of maps to the right young men, and they soon discovered the wrinkles in the face of Weather."[20] If we include the dynamic climatology of Tor Bergeron, we might also add, "wrinkles in the face of climate." Collectively, Bjerknes and his associates championed something larger than themselves, something useful and entirely new, a set of graphical methods to analyze and predict short-term changes in the weather. They worked diligently to spread their theoretical insights internationally, to collect and interpret more and better observations at higher and higher altitudes, and to codify graphical techniques of air mass analysis and weather forecasting for the use of national weather services.

Further Unraveling the Knot

Weather and climate were intimately connected in the work of Carl-Gustaf Rossby (1898-1957), who brought the Bergen methods to the United States, developed new methods of collecting atmospheric measurements aloft, and connected geophysical fluid dynamics with the practical needs of aviation and forecasting. Rossby established the first commercial airlines weather forecasting system and built the first graduate program in meteorology at M.I.T. in 1928 along with a connection to dynamic oceanographers at

[19] Henri Poincaré, *Science et méthod* (Paris: E. Flammarion, 1906).

[20] Robert Marc Friedman, *Appropriating the Weather: Vilhelm Bjerknes and the construction of a modern meteorology* (Ithaca: Cornell University Press, 1989); Tor Bergeron, Tor, Olaf Devik, and Carl Ludvig Godske, "Vilhelm Bjerknes, March 14, 1862 - April 9, 1951," *In Memory of Vilhelm Bjerknes on the 100th Anniversary of His Birth,* A. Eliassen and E. Hoiland, eds., *Geofysiske publikasjoner* 24 (1962): 7-25, quote from 18.

Woods Hole in 1930. He supervised the training of literally thousands of aviation cadets during World War II, developed a general theory of long waves and jet streams in the upper atmosphere, and established the University of Chicago school of geophysics and the Institute of Tropical Meteorology at the University of Puerto Rico. After the war, he placed the American Meteorological Society on a professional keel by founding the *Journal of Meteorology* and, working closely with Jule Charney, stimulated work on numerical weather prediction at the Institute for Advanced Study. In the final decade of his life, Rossby returned to his native Sweden, establishing the International Meteorological Institute in Stockholm where he worked on global environmental issues. In his signature contribution, he identified upper-air planetary (or Rossby) waves as potential keys to long-range prediction, treating them as idealized cases suitable for computation by digital computers.

One of Rossby's first projects in America in the 1920s was the construction of a rotating tank experiment in the basement of the U.S. Weather Bureau, a model of hemispheric circulation scaled to emulate the large-scale dynamics of the atmosphere. In this he was inspired by Helmholtz's hydrodynamical theory of vortex motions, Felix Exner's dishpan experiments, and the "principle of similar movements."[21] Rossby's tank was two meters in diameter, filled with colored fluids of different densities, and rotated three to four times per minute. Like the atmosphere, the rotating tank had large horizontal dimension compared to its vertical depth. To a first approximation, it was two-dimensional. This was the key to his theoretical approach. Although the tank suffered mechanical failure, and his initial attempt to emulate the atmosphere and write non-dimensional equations of its motion was inconclusive, this line of research eventually proved fruitful in the late 1940s when Dave Fultz (1921-2002) at the University of Chicago employed a two-layer wave tank to produce experimental results that informed numerical analysis of the large-scale circulations that occur in the Earth's atmosphere and oceans.

For Rossby, the research frontier was theoretical, and it circulated at the 500-millibar level (an altitude of about 5.6 kilometers). The upper-level winds and planetary waves looked and behaved very much like the colored fluids in the wave tank experiments. They had the distinct advantage that, unlike surface weather conditions, the flow at high altitudes was, to a first approximation, frictionless and devoid of the complicating factors of water vapor, clouds, and diurnal heating. That is to say, the equations of motion were rather simple to write and were well- behaved over longer periods. This provided hope for longer-range forecasts, and, when digital computers first became available, for tractable calculations that could be accomplished faster than the weather was changing; that is to say, for operational numerical weather prediction.

In his later years, Rossby actively pursued numerical weather prediction in Sweden in an era in which there was no Swedish word for digital computer. There he supported the first operational numerical forecast in the world generated by the BESK computer. He was fully engaged at the cutting edge of research, maintaining a large correspondence network of colleagues and welcoming visitors to the International

[21] Felix Exner, *Dynamische Meteorologie*, 2nd ed. (Vienna: Julius Springer, 1925), 341; C.-G. Rossby, "On the Solution of Problems of Atmospheric Motion by Means of Model Experiments," *Monthly Weather Review* 54 (1926): 237–240.

Meteorological Institute in Stockholm.[22] Rossby's work took a global, environmental turn in the mid-1950s as he turned his attention to climate. He fostered new conversations among geoscientists of all stripes: oceanographers, geographers, and geologists. Moving onto issues of geophysics and global pollution, he founded the international environmental journal *Tellus*. He was interested in climatic change and variability on all time scales, including the grand cycles of ice ages and interglacials. He spoke increasingly of the atmosphere as a milieu, directly influencing all of human experience and warned of the increasing stress pollution was placing on it. He stood in awe of the atmosphere's dynamical and chemical complexity and called for an attitude of respect, "for the planet on which we live." He eagerly anticipated the coming breakthrough, "a grand era in meteorology," when artificial satellites can view the atmosphere from above. "Right now, we are like crabs on the ocean floor, he said. "What we need is a view from a satellite. Only from a satellite can we see the planetary waves."[23] His best student, Harry Wexler, was, just then, in the process of developing such capacity.

Using Technology to Cut the Gordian Knot

Harry Wexler (1911-1962) introduced a number of transformative technologies into meteorological practice, including radar, nuclear tracers, digital computers, sounding rockets, and weather satellites, that helped cut into, if not through, the Gordian Knot of prevision. This was the legendary "Alexandrian solution," alluded to by Rossby in 1956, when he wrote, "Technology is cutting the Gordian Knot instead of untying it."[24] Still, theorists held out hope for more and more accurate measurements and a more perfect model, perhaps driven by large and fast computers. On this foundation, Wexler and his many colleagues, notably Jule Charney, prepared the foundations for the emergence of the interdisciplinary atmospheric sciences.

As an employee of the U.S. Weather Bureau, Wexler worked to bring air mass analysis to the United States, and, as an army air force officer, worked with Rossby to train a generation of weather cadets during World War II. After the war, Wexler became head of research in the weather bureau where he nurtured every new technological development and every new international program of relevance to the atmosphere. In this capacity, he worked to incorporate radar, sounding rockets, nuclear tracers, digital computers, and satellites into meteorological practice. He demonstrated scientific leadership as a member of (and often chair of) many national and international meteorological advisory committees, including the U.S. military's Research and Development Board, the Advisory Committee on Reactor Safeguards for the U.S. Atomic Energy Committee, and the National Research Council's Space Science Board. Wexler's vision was global, as evidenced by his leadership during the International Geophysical Year of 1957-58. He conducted experiments and coordinated measurements on the Antarctic ice sheet and established the weather bureau's Mauna Loa Observatory, which measured the concentrations of carbon dioxide and other trace gases. In 1962, the year of his untimely death, Wexler was on assignment from the Kennedy Administration,

[22] Bert Bolin, "Carl-Gustaf Rossby: The Stockholm Period, 1947–1957," *Tellus* A–B 51 (1999): 4–12.
[23] "Man's Milieu," *Time* 68 (Dec. 17, 1956), 68-79.
[24] C.-G. Rossby, "Current Problems in Meteorology."

negotiating the World Weather Watch, a lasting international agreement on the peaceful exchange of weather information.[25]

Wexler's position allowed him access to the full range of atmospheric technologies. Radioactive clouds generated by outdoor nuclear testing introduced new tools that cut across the vast spectrum of atmospheric processes and, as Wexler put it, provided meteorologists with a "matchless tracing agent" of horizontal and vertical flow and diffusion applicable at all scales and all levels, from the surface layer to the stratosphere.[26] At higher levels, the radioactive clouds sketched out the patterns of Rossby waves. Wexler also used the new technology of weather radar to determine the structure of a hurricane that passed over Florida in 1945. He contrasted traditional observational and synoptic mapping techniques with time-lapse images and tracking provided by high-resolution, long-range military radar. The images revealed hitherto unseen details of squall lines and hurricane bands and stimulated novel explanations of their dynamics. Wexler pointed out that the radar screen was now providing a new "eyepiece" thorough which to view severe weather and was opening up a new research field involving radar in meteorology.[27] Wexler also served as weather bureau liaison for the Institute for Advanced Study computer project in Princeton, New Jersey, a project led by John von Neumann to investigate the theory of dynamic meteorology in order to make it accessible to high speed, electronic, digital, automatic computing. Subsequently, Wexler was in charge of institutionalizing and operationalizing numerical weather prediction and general circulation modelling within the U.S. Weather Bureau. Sounding rockets came under Wexler's purview as scientific probes and observational platforms to investigate the upper atmosphere and photograph clouds from above. Wexler served as chair of several influential committees on this subject, and his extensive records from meetings show the evolution of issues, including the official naming of the new atmospheric layers being discovered.[28] The meteorological satellite era, long anticipated by Rossby, officially began on April 1, 1960, when TIROS 1, the first Television and Infra-Red Observing Satellite, reached orbit. TIROS 1 carried two shuttered television cameras (photosensitive vidicon tubes) that recorded images of clouds on tape for later transmission to the ground. Wexler served as chief scientist for the program.

Technology aside, the question remains: What can be accomplished and what cannot, especially in forecasting and prediction? Techniques pioneered by the Bergen school made it possible to forecast partial rotations of a single vortex, initially for two to three days and later, with some skill, for three to seven days. However, it is not possible, due to turbulence and non-linear interactions, to forecast multiple rotations of multiple vortices, that is, to generate a long-range weather forecast for periods of weeks, months,

[25] J.R. Fleming, "Polar and Global Meteorology in the Career of Harry Wexler, 1933–1962," *Globalizing Polar Science: Reconsidering the social and intellectual implications of the International Polar and Geophysical Years,* R.D. Launius, J.R. Fleming, and D.H. DeVorkin, eds. (New York: Palgrave, 2010), 225-241.

[26] Harry Wexler, "Introductory Talk," Conference on Atomic Energy and Meteorology, U.S. Weather Bureau, December 19-20, 1949, Harry Wexler Papers, box 16, U.S Library of Congress, Manuscript Division.

[27] Harry Wexler, "Structure of Hurricanes as Determined by Radar," *Annals of the New York Academy of Sciences* 48 (1947): 821-844.

[28] "Notes on Upper Atmospheric Nomenclature," Harry Wexler Papers, box 32, U.S Library of Congress, Manuscript Division.

or seasons. Prediction of planetary, or Rossby wave upper-air patterns, have been extended to five to seven days. Still, scientists may know where the ridges and troughs are, but cannot anticipate all their changes and vicissitudes with perfect certainty. In climate-related affairs, an "infinite forecast" can provide the overall patterns and the statistics of the general circulation, but at the expense of all detail. Yet it is not possible to predict the future state of the perturbed climate system, whether from natural or human causes, let alone the behavior of weather systems or even modified clouds. We can intervene in natural systems, but we cannot control them, nor can we forecast them with any precision. The best scientists can do is to gauge sensitivities to changes in various factors that make up the models.

An influential report noted in 1962, "The task of the atmospheric scientists is to make quantitative measurements of the properties that *describe* the atmosphere's successive states, to *understand* the physical processes by which the successive states are determined, to *predict* future states, and, if feasible, to *influence* future states in a beneficial manner."[29] Atmospheric scientists have addressed the first two tasks and have generated robust progress; the final two tasks, prediction and influence (or control) remain beyond their reach. Finally, they are helpless (not a word often used in science) to predict the timing of regime changes, or changes of state of the flow.

New Knots

The neo-Laplacian program hit a solid brick wall in 1960 when, using a small computer and a simple non-linear model, Edward Lorenz (1917-2008) introduced chaos theory into meteorology and by extension into climate modeling.[30] He brought the novel understanding that chaos theory provided a new topology, an extreme sensitivity to initial conditions in a dynamical system of deterministic non-periodic flow.[31] In chaos theory, future states of the weather and climate then become identifiable with the attractor of the dynamical system — but the dynamical system may have more than one attractor! No matter how sophisticated the technology becomes, chaos theory holds that perfectly accurate measurements and perfectly accurate forecasts will never be possible.[32]

Atmospheric scientists since face a number of difficult conceptual choices as they come to grip with chaos theory and the challenges it poses for both weather and climate modeling. The technologies that propelled the profound transformation of atmospheric research during and just after World War II, are, in their improved versions, still in widespread use. Each made significant cuts into the Gordian Knot of meteorology, perhaps none greater than improvement of forecasting skill due to the ultimate linking of satellite monitoring and numerical weather prediction. Ensemble forecasters too attempt to circumvent chaotic limits by using spaghetti plots of multiple model forecasts to reduce uncertainty. Yet the neo-Laplacian knot persists and a new chaotic knot has been identified, clearly recognized in the field of numerical weather prediction, but still only

[29] Sverre Petterssen, "The Atmospheric Sciences, 1961-1971*,"* *Weatherwise* (Oct. 1962): 185-187, 213.
[30] Edward N. Lorenz, "The Statistical Prediction of Solutions of Dynamic Equations," Proceedings of the International Symposium on Numerical Weather Prediction in Tokyo, November 7-13, 1960, S. Syono, ed. Tokyo: Meteorological Society of Japan, 1962.
[31] Edward N. Lorenz, "Deterministic Nonperiodic Flow," *J. Atmos. Sci.* 20 (1963): 130–141.
[32] Edward N. Lorenz, *The Essence of Chaos* (Seattle: University of Washington Press, 1993).

dimly apprehended with regards to climate models. In 1994 J. B. Elsner and J.C. Honoré noted that almost two decades elapsed following the seminal work of Lorenz before the larger scientific community engaged with the quantitative implications of chaos theory in any serious way.[33]

In one of his many lectures, Lorenz addressed the issue of "Solving the weather forecasting problem." He shared three possibilities:

1. Learning to make essentially perfect weather forecasts.
2. Learning to make the best attainable weather forecasts, even if they are far from perfect.
3. Learning how good the best attainable forecasts are even if we don't learn how to make them.

Then, with a twinkle in his eye, Lorenz asked, "Why should nearly perfect forecasts be unattainable?" — "Chaos."[34] Option 1. is where we were; option 2. is where we are; and option 3. represents the future. In effect Lorenz had identified a new Gordian Knot of meteorology to accompany the older one that had been somewhat unraveled and frayed, but not untied. The atmospheric sciences are still coming to terms with this challenge.

In 1927 Sir Arthur Eddington said this about the new and revolutionary quantum theory of matter: "Our eyes once opened, we may pass on to a yet newer outlook of the world, but we cannot go back to the old outlook." This implicit acknowledgment of shape-shifting concepts in science applies equally well to new and emerging understandings of weather and climate, as informed by chaos theory.

[33] J. B. Elsner and J. C. Honoré, "Ignoring Chaos," *Bulletin of the American Meteorological Society* 75 (1994): 1846-1847.
[34] Undated lecture transparency in the Papers of Edward N. Lorenz, U.S Library of Congress, Manuscript Division.