CLEVELAND ABBE AND AMERICAN METEOROLOGY, 1871–1901

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A reexamination and reappraisal of Cleveland Abbe's role in the development of meteorological science and services is made.

Fig. 1. Cleveland Abbe (1838–1916).

"*[to Abbe] we are indebted for the very existence of the Weather Bureau.*"

—BRIGADIER GENERAL WILLIAM B. HAZEN
(testimony before Congress, 1886)

In 1871 Cleveland Abbe (1838–1916) took a risk and joined the U.S. Government's completely new weather service as its first chief meteorologist. This move took him from the well-established field of astronomy into what was then a developmental science. He brought to the endeavor scientific rigor and a far-reaching vision of worldwide scientific cooperation. From the outset he focused on two major scientific goals: the optimization of the weather service, and the study and advocacy of theoretical meteorology. As he tutored the neophytes at the headquarters in Washington, D.C., he symbolized for them what they might achieve as meteorologists (Reingold 1964). During the formative years of government weather services, he fostered, and in some respects embodied, the essential linkage between institutional and theoretical development (Fleming 1990). In that role he came to recognize the three dimensions of meteorology: forecasting, climatology, and physical theory. He brought together his insights in 1901. In a comprehensive scientific paper, published in the *Monthly Weather Review* (*MWR*), he argued against long-range weather forecasts based on empirical methodology, by which he meant forecasts that are "generalizations based upon observations" without the benefit of physical theories (Abbe 1901). Instead, he proposed an integration of the basic equations of physics and fluid dynamics, and laid out the mathematical means by which this might be accomplished. Just over a century later we examine anew his organizational work and his contributions to the progress of theoretical meteorology, and suggest a revised appreciation for his place in the history of meteorology.

A number of recent studies review the evolution of weather services in Europe during the last half of the nineteenth century. They describe developments in the United Kingdom, France, Belgium, and what was then Prussia that provided the context for American efforts in the post–Civil War era. Read in their entirety, with some oversimplification, one finds in Europe at the midcentury that "meteorology still rested on a fractured and incomplete theoretical foundation that tried vainly to explain and relate a multitude of complicated and inter-dependent phenomena" (Davis 1984). From that point the science, initially embedded in astronomy, developed unevenly and empirically, inhibited by national politics and internal squabbles. In Belgium, Adolphe Quetelet had founded the Brussels Observatory in 1823, but he "did not...become an astronomer; rather he became a meteorologist." Then, instead of making a name for himself in meteorological theory, he transitioned into sociology and statistics (Stigler 1999). In France the Paris Observatory controlled meteorology from the midcentury until 1878. During that period the overturn of governments, war, and internal staff tensions constrained progress. Notably the chief meteorologist, Edmé H. Marié-Davy, chafed under the thumb of Urbain Leverrier, the observatory's director (Davis 1984). In Prussia, Heinrich Dove, the preeminent meteorologist of the nineteenth century, took over the Prussian Meteorological Institute (PMI) in 1849. In spite of a promising start, his focus on climatology and his resistance to new scientific findings inhibited the development of meteorology. In fact, with Chancellor Bismarck's approval, the PMI offered no daily forecasting service into the 1870s (Bernhardt 2004). One observer has characterized British meteorology at the midcentury as being immature; its "irregular far-spread surface was dotted with cultivation chosen without discrimination and treated with no common principle." Robert Fitzroy, the head of the meteorological department from 1854, "gained considerable authority" for his empirical predictions, but criticism for his lack of theoretical principles contributed to his suicide in 1865 (Anderson 2005; Davis 1984).

Across the Atlantic at the midcentury American meteorology evolved unevenly as the work of the U.S. Army Medical Corps, the Smithsonian Institution, and others who built observational networks and focused on climatology. Theoretical works by Redfield, Espy, Loomis, and Ferrel advanced the science, but the nation lacked an academic infrastructure dedicated to the science of meteorology. Moreover, those theorists, unlike many of their European counterparts, neither came from astronomy nor attained advanced degrees in the sciences. Then in 1861 the Civil War temporarily disrupted progress in the subject. Thus, when Congress in 1870 mandated the formation of a national weather forecasting service it charged the War Department with the responsibility of establishing an entirely new agency. The Secretary of War and the Army Commander accepted the task reluctantly because it was outside their normal sphere. The job fell to the Signal Service, the peacetime successor to the Signal Corps (Fleming 2000). Brigadier General Albert E. Myer, Chief Signal Officer (CSO), early in 1871 hired Abbe, and the two set up operations in Washington, D.C. Myer provided the manpower, assigning junior officers and recruiting enlisted personnel. Abbe, by example and precept, established the scientific standards for the service. Myer made a fortunate choice; Abbe had studied astronomy under Franz Brünnow at the University of Michigan and spent two years as a supernumerary astronomer under Otto Struve at the Nicholas Central Observatory in Pulkovo, Russia. He had then assumed a position as director of the Cincinnati Observatory where he conceived and managed a private meteorological service for several months (Abbe 1955; Fleming 1990; Humphreys 1919).

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FORECASTING AND VERIFICATION.

Of practical necessity Abbe addressed the forecasting dimension of modern meteorology at the outset. Predicting the weather required a widespread but highly coordinated team of observers and forecasters. Organization was key. From early in 1871 Myer and Abbe applied themselves energetically to building a national reporting system. Abbe promptly initiated the reporting and forecasting procedures. In developing the reporting protocols Abbe selected data-collecting instruments critical to the success of the new enterprise, and trained the Army's observer sergeants in their use. They transmitted data from the field using forms and protocols adapted from those that Abbe had developed while forecasting the weather from Cincinnati, Ohio. The information arrived by telegraph coded to maximize accuracy and minimize the word count and charges. The reports piled up in a rush at the appointed hours. A team of clerks recorded and decoded the messages, then manually entered the data onto weather maps. With those maps the forecast officer issued his predictions—an entirely empirical process (Monmonier 1999; Weber 1922). Abbe personally issued the first official weather forecast on 19 February 1871. He continued forecasting alone for the first six months of 1871 while training additional staff. At midyear 1871 three other forecasters joined the action: two army lieutenants and a civilian professor, Thompson B. Maury. By rotating the workload across a team of forecasters, Abbe avoided flare-ups like that at the Paris Observatory in 1864 when Director Leverrier sacked Marié-Davy for refusal to remain on duty all day until midnight (Davis 1984).

Abbe demanded precise language in the forecasts, covering four key meteorological elements [weather (clouds and precipitation), temperature, wind direction, and barometric pressure] for each geographic division. He directed that the first sentence of a probability (the term in those days for "forecast") must contain a verb in a future tense, for example, "the barometer *will rise* . . ." Moreover, he forbade the use of terms such as "mostly" and "possibly," requiring instead explicit terminology describing expected conditions (Abbe 1873). Three times daily the duty forecaster broadcast a synopsis of prevailing weather conditions nationwide, along with the "probabilities" of weather in the next 24 hours (later extended to 36 hours). Sixty-odd copies of the weather charts went to Congress, the press, and various scientific institutions. By 1872 Abbe regularly sent over 500 sets of the daily maps and bulletins overseas in exchange for data from foreign meteorologists (Abbe 1893b; CSO 1871, 1872).

As a means of ensuring quality performance Abbe insisted on verifying the predictions. Within three days after issuing a set of probabilities the duty officer in Washington compared the preceding forecasts with the corresponding synopses of observed weather conditions. For each geographic district the verifying officer determined three times daily the degree of fulfillment of the forecast for each of the key elements: weather, temperature, wind, and pressure. During the first year of operation in 1871, Abbe and his staff verified 69% of the predictions. The annual report apologized for the 31% that missed the mark, citing the pressure of time as the cause. (The midnight observer reports reached Washington at 11:35 P.M. local time, and the forecaster had only 90 minutes to release probabilities to the press.) In 1872 the indications officers (forecasters) improved performance, enabling them to claim verification of 76.8% of their predictions. By their calculations the number rose to 89.1% in 1883 then declined to 80.9% in 1887. The CSO blamed the turnover of experienced indications officers for the results after 1883 (CSO 1871, 1872, 1887).

Abbe required the weather service to stay at the forefront of technology. He procured "[standard] and ingeniously devised instruments . . . from Europe and from meteorologists in the [U.S.]." Over time the instrument division at headquarters tested and calibrated thousands of devices, and technicians even designed and built instruments. Self-registering equipment came into use, and by the end of the century the United States had 114 class I (automatic recording) observation stations—five times the number of the runner up, Austria (Bartholomew 1899). Anticipating increased international cooperation in the 1880s, Abbe sought quality instruments calibrated to international standards. He turned to Wolcott Gibbs at Harvard and Arthur Wright at Yale to design improved equipment. For comparison purposes he ordered a barometer from Heinrich Wild, director of the Nicholas Central Observatory in Russia. From Germany he sought an anemometer and several types of hygrometers. Not to be outdone by Fitzroy and Marié-Davy, each of whom had invented a meteorological instrument, Abbe invented an anemobarometer to test the effect of chimney and window drafts on barometers within an enclosed space (CSO 1871, 1881, 1882, 1884a).

The voluminous annual reports of the CSO make clear that Abbe provided scientific leadership for an extensive organization. He excelled at setting standards, demonstrating techniques, and teaching. He focused on details, and as a perfectionist chose to do it himself rather than delegate. Note a case in point: he assumed responsibility for computing tables converting altitudes of all observer stations to sea level equivalents. It took him 10 years to complete the task, in addition to his other duties, when he could have delegated the project (Abbe 1893b, CSO 1884b). Nonetheless, the Signal Service grew rapidly, and at its height in the 1880s recruited, trained, and employed as observers over 450 sergeants and corporals, and incorporated into the reporting system 300 civilian volunteers from the defunct Smithsonian observer system. The service had established 541 observation stations across the United States. It operated 3000 miles of noncommercial government telegraph lines in addition to its contract with Western Union. In Washington the staff prepared forecasts for 41 states and districts daily. In addition, 45 regional observers made local forecasts (CSO 1884b).

STANDARD TIME. Accuracy in forecasting depended on the accurate timing of observations. At first weather observers used local time because no system of standard time existed, either in the United States or abroad. Local time often meant railroad time, and that could vary as much as 20 minutes from the time proper to the local meridian. Abbe called for change, emphasizing the need for simultaneous readings by Signal Service observers in order to construct accurate charts and weather maps. In 1875, he recommended to the president of the American Metrological Society the establishment of a committee on standard time. The president appointed him chair. The American Association for the Advancement of Science (AAAS) and others supported the objective. Abbe's report in 1879 recommended the system of meridians that is now in general use. Political support from the railroads proved critical. Railroad dispatchers experienced huge safety problems from inaccurate time. At a meeting in 1883 of the General Time Convention of railroad officials, William F. Allen, the convention's secretary, secured the adoption of a system of time meridians one hour apart across the country, anchored on the Greenwich prime meridian. The movement gained momentum and Abbe's approach "ultimately led to the adoption of Standard Time in the United States" on 18 November 1883 (Bartky 2000; Galison 2003). From Abbe's perspective, however, the full potential for dynamical weather prediction would not be achieved without standard time worldwide. With his prodding Congress in 1882 passed a resolution written by Abbe authorizing an international conference on standard time. Abbe served as the Signal Service delegate to the conference in 1884 in Washington. The conferees adopted in principle the system of hourly meridians for use worldwide based on the prime meridian running through Greenwich (CSO 1881, 1884, 1885; Abbe 1893b).

CLIMATOLOGY. Climatology, a second dimension of meteorology, captured Abbe's attention early on as he and the staff sought to establish physical baselines, a considerable empirical effort. They needed climatologies for historical perspective on rainfall, frosts, storm tracks, winds, auroras and geomagnetic storms, and upper-atmospheric conditions. In June 1871 Abbe requested meteorological data from ocean observers and General Myer forwarded the request to merchant ship owners and captains. The Secretary of the Navy cooperated by ordering daily meteorological readings aboard all naval vessels. With these maritime observations in hand Abbe wrote an article on North Atlantic storms, fog, and ice conditions. In the same period he set in motion a study of clouds using photography, and in 1872 wrote a report on "Methods of observing clouds." Responding to another congressional mandate in 1872 the Service inaugurated water-level readings on the rivers and Abbe commenced flood predictions. In 1873 he prepared "charts of statistics on storm frequency and climatic characteristics," which appeared in the *Statistical Atlas of the U.S.* From that exercise he first discovered the existence of a region of special storm frequency in Kansas and Nebraska (Abbe 1874). He led a party to Pikes Peak in 1878 to observe an eclipse of the sun. While there he gathered data for a study in hygrometry, and studied the effect of barometric pressure on psychrometer readings. The following year he used weather charts to determine the average direction and velocity of barometric lows, average barometric pressure, the most frequent wind direction before rainfall, and the frequency of rainfall by the month. In short, he maintained a whirlwind of scientific inquiry (Abbe 1893b, CSO 1872, 1873, 1878, 1879).

TRANSFER OF SCIENTIFIC KNOWLEDGE. In order to disseminate American weather data more effectively Abbe founded *MWR* in 1872. The French had initiated the *Bulletin Météorologique Internationale* a decade earlier for the same purpose. At the same time he sought to collect and publish worldwide simultaneous weather observations. The Chief Signal Officer carried Abbe's proposal for international cooperation in this project to the first International Congress of Meteorology at Vienna in 1873 and got agreement. Weather data from most of the world's collection agencies flowed into Washington. Two years later Abbe began publishing it in the *Bulletin of*

International Simultaneous Observations. He proudly called it "the finest piece of international co-operation in scientific work that the world had ever seen . . . ." The *finest* perhaps, but not the *first,* because a century earlier in Europe the *Societas Meteorologica Palatina* had a network of 30-odd observation stations sharing data (Cassidy 1985). Continuing his international focus, Abbe exchanged and collected worldwide books and scholarly writings on meteorology to form a professional library. By 1887 the collection had grown to 53,770 titles [most of which are now at the National Oceanic and Atmospheric Administration's (NOAA's) main library] (CSO 1887). He published over 290 articles and books. The topics ranged across mathematics, climatology, geodesy, solar heat, eclipses, auroras, standard time, storms, comets, locust migration, astronomy, barometric reductions, instrumentation, tree growth, magnetic observations, earthquakes, atmospheric electricity, clouds, rain, forecasting and verification, cold waves, frost and ice, biographical sketches, and most of all meteorology (Humphreys 1919). Through his voluminous correspondence and data sharing he kept the American weather service in the spotlight internationally. He stated later that "[t]he whole service is recognized the world over as a model in respect to thoroughness, accuracy and promptness." Piazzi Smyth, Astronomer Royal of Scotland, wrote in 1883, "the enormous scale of your Army Signaling Office . . . quite takes one's breath way in astonishment and admiration!!!" (Smyth 1883). The momentum in the weather service thus moved American meteorology from the periphery to the center of worldwide meteorological development where it remained to the end of the century (Palló 1995).

As American universities gradually built up the physical sciences in the late nineteenth century, government-sponsored science served as a senior partner in research and the economy. Pace setters such as the Smithsonian Institution, the U.S. Geological Survey, the Coast and Geodetic Survey, and the Army Medical Corps led the way (Dupree 1957). At a time when American universities did not recognize meteorology as a separate science, the Signal Service offered "advanced in-service training," which might be termed "America's first postgraduate program in meteorology . . . ." (Koelsch 1996). In addition, Abbe wrote articles urging schools to offer meteorology and disseminated curricula for the study of meteorology at both the secondary school and college levels. Then in 1893 Columbian University (now George Washington University) inaugurated a graduate school and appointed Abbe [adjunct] professor of meteorology. On a part-time basis he supervised "candidates for the M.S. degree." Five years later Johns Hopkins University appointed him [adjunct] lecturer in meteorology (Humphreys 1919).

ABBE'S THEORETICAL EXPLORATIONS.

The Myer era at the Signal Service ended with his death in 1880. Brigadier General W. B. Hazen (1830–87) succeeded as CSO. Myer eschewed scientific research; Hazen supported it, especially in staffing. In 1882, with his approval, Abbe recruited William Ferrel, by then a well-established geophysicist. Ferrel's "work was the basis of [Abbe's] 'probabilities' in Cincinnati and Washington . . ." (Abbe 1891). Ferrel had studied the effect of the Earth's rotation on the general circulation of the atmosphere and oceans, and in 1858 postulated Ferrel's law (Ferrel 1858). His joining the meteorological staff considerably enhanced the scientific program of the Signal Service. Two years later Abbe brought in Thomas C. Mendenhall, a physicist at Ohio State University, who had organized the Ohio Weather Bureau. At the Signal Service Mendenhall established a physics laboratory for experimental investigation, while Abbe retained responsibility for theoretical meteorology (Abbe 1883).

Abbe's work in the third dimension of meteorology occurred primarily in the "Study Room" (originally his personal office). From 1871 the Study Room constituted a laboratory for the development of theoretical meteorology. As weather data flowed in Abbe dealt with numerous analytical questions and began a variety of studies on meteorological topics. He justified the research emphasis, noting that experience demonstrated "very forcibly the need of a special organization for the purpose of investigating the numerous questions that arose in . . . the daily work of the Service." The public asked "questions, sometimes involving difficult points in meteorology . . . [that] demanded extensive research . . . ." In one area the emphasis on geomagnetic and electrical phenomena proved quite practical; auroras and geomagnetic storms frequently knocked out the early telegraph lines. He argued that "there was a general desire, both in and out of the Service, that we should undertake such investigations into the laws of the motion of the atmosphere as would sum up the advances that meteorology was steadily making through the labors of the numerous weather bureaus of the world" (Abbe 1893b).

With these various initiatives underway, Abbe had occasion to reflect on the nature of weather itself. In the first year of operation, after Abbe had inaugurated weather maps three times daily, he discovered an empirical connection between cold waves and what he called northers flowing over Texas to the Gulf of Mexico. Based on empirical analysis he produced his first formal meteorological finding. In 1871 he published his "law of the motion of storms," which he originally discussed with Joseph Henry in 1867 and enunciated in 1869 at the Cincinnati Observatory:

> Local currents arising in this surface stratum of air feed the central area of condensation, which soon becomes hazy, and then cloudy until rain begins. While the general progress of the storm-center will be northeastward, yet it is evident that wherever the moistest air exists, there the condensation will take place most rapidly; there the barometer will also fall the most rapidly; and thither the storm will be strongest drawn (Abbe 1893b; CSO 1871).

Abbe's conjecture resembles the exploratory, tentative European finds of that era, for example, Dove's law of (wind) rotation in 1827, C. H. D. Buys Ballot's law relating pressure and wind in 1857, and R. H. Scott's studies in 1868 on the same subject (Davis 1984). Beyond these empirical efforts, however, Abbe operated on another level, using his knowledge of Ferrel's work of the 1850s in dynamical meteorology. Employing those primitive but nonetheless theoretical principles, he claimed success in many weather predictions such as the "second hurricane of August, 1871," at a time when he and the Signal Service lacked the experience to have constructed empirical rules for such predictions. Through all of this Abbe treated meteorology as a complex of concepts, process, and structure. Cannon (1978) defines Abbe's approach as "Humboldtian science," a complex including "astronomy, the physics of the earth and the biology of the earth all viewed from a geographical standpoint, with the goal of discovering quantitative mathematical connections . . . ."

Friedman (1989) states that by the end of the nineteenth century, "the dream of finding simple laws for predicting weather faded." He characterizes meteorologists of that period, who sought statistical patterns rather than physical or dynamical insights to predict the weather, as disillusioned, and as developing a sense of hopelessness. Those may be correct generalizations, but Abbe resists such a characterization. Though Abbe used empirical techniques to make daily forecasts, he neither naïvely endorsed these as sufficient in themselves, nor did he think that a diligent search would indeed reveal some simple, overarching law. Instead, his writing and actions suggest that he realized from the beginning the need for a comprehensive physical theory. He understood that theoretically sound forecasting required upper-air measurements beyond the technological capabilities of his time, and beyond the mathematical tools at hand; hence, his continued interest in balloon studies, mathematics, and fundamental fluid dynamics.

ABBE'S TRANSLATIONS. Abbe closely monitored scholarship in meteorology and played an extraordinary role for several decades as a primary conduit of information between the European and American research communities. Kevles (1979) argues that during this period American physicists fell behind European physicists in part because of their lack of the necessary mathematical skills, and because they did not keep abreast of European scientific journals. No such constraints inhibited Abbe. He assiduously studied scientific articles, especially those in German in which he was fluent, and one may infer the direction of his thinking from the papers that he chose to translate and publish worldwide. At a time when there was no concise treatise on dynamical meteorology, Abbe drew together collections of papers on the subject. Before 1917, Abbe's publications provided the only concentrated examination of the subject available on either continent. His *First Collection* of 10 scientific articles focused on the initial investigations of the role of water phase transformations in driving cloud development. He included one of Ferrel's papers along with nine others from Europe, all of which had a heavy mathematical content (Abbe 1878). These papers examined two subjects: a) the dynamics of moist atmospheric convection in the vertical, which is the fundamental basis for the thermal theory of cyclones, and b) the dynamical theory of winds and currents on a rotating Earth. In this and subsequent collections Abbe imposed his own thinking implicitly by his selection of papers, and by the revealing commentary in his footnotes. He continued to promote dynamical meteorology and underscored Ferrel's dynamical approach to weather prediction. Abbe thought that Europeans paid too little attention to Ferrel's work. Although Fitzroy in the United Kingdom knew of Ferrel's writing, French meteorologists remained unaware of it into the 1870s (Davis 1984). For the most part, Abbe translated with a light touch, but he sought to make the science more definitive, or to describe the limitations of the papers, especially where they tended to undermine Ferrel's claim to primacy. Though younger, Abbe served in many ways to bolster Ferrel's career and his standing within the scientific community, serving as both mentor and colleague (Kutzbach 1979).

Hazen died in 1887 and Brigadier General A. W. Greely (1844–1935) replaced him as CSO. Greely, formerly a junior officer at the Signal Service, had achieved fame as commander of the ill-fated Lady Franklin Bay Expedition in 1881–84 (Guttridge 2000). He sought to overhaul the Signal Service to address criticisms generated by the Congressional hearings of the Allison Commission (1886) that examined all of the government's scientific agencies for potential efficiencies. He directed Abbe to report on the "practical applications of theoretical laws to weather prediction" in order to blunt the charge that the Signal Service engaged in unnecessary scientific research. Abbe took up the challenge, assembling data and notes that had "accumulated for a number of years." From this he outlined a book on storm prediction, including chapters on "mechanical laws deduced" and "empirical laws converted" (Abbe 1887). The first fruits of that study appeared as an article entitled "Recent progress in dynamic meteorology," in the Smithsonian Report of 1888 (Abbe 1890b). A year later he produced a far more advanced text: *Preparatory Studies for Deductive Methods in Storm and Weather Predictions.* Abbe sought to provide "an approximately complete rational system in meteorology, *a deductive or philosophical method,* in which the pertinent physical laws shall be followed out to their conclusions . . ." [italics added] (Abbe 1890a). In this book, Abbe treated friction and vortex motion, horizontal (turbulent) airflow, buoyant motion, and the buoyant and horizontal motion of clouds, as well as the mechanics of storms. Thus, by 1890 Abbe had moved well beyond simple empirical approaches to state firmly that "[m]eteorology is essentially the application of hydrodynamics and thermodynamics to the atmosphere of the earth . . ." Three years later Abbe suggested that meteorological analysis "should be perfected by experimental work similar to that done in the physical laboratories, and by mathematical work similar to that done in astronomical institutions. It is high time that we began to pass from the empiric to the philosophic methods . . ." (Abbe 1893c). Abbe propounded these views at a time in which the young Norwegian and future meteorologist, Vilhelm Bjerknes, was still hoping to make a name in physics (Friedman 1989).

In 1888 Abbe previewed a second set of translations of papers by European meteorologists, preponderantly German. He said that his research had been "almost wholly directed to the dynamical phenomena . . . in the movements of the atmosphere," and that such questions were the most important to the "practical meteorologist." Speaking of the forthcoming *Second Collection,* he said that the articles "are so important and so little accessible to American readers . . . that I have prepared full translations of them," hoping thereby to engage American scientists in studies then pursued "by the most successful European students." He noted the requirement for close scientific attention in applying fundamental laws to "the superficial phenomena of nature." Citing the universal difficulty in analyzing the "motions of the atmosphere," Abbe cheered the advances made through applying thermodynamics and the study of fluid motions. He foresaw "a lasting superstructure of dynamic and rational deductive meteorology. *But such work needs the co-operation of many minds*" [italics added]. He then elaborated on the "minds" needed to solve the very complex problem of atmospheric mechanics: those of hydraulic engineers, astronomers, chemists, physicists, and mathematicians. Abbe concluded his advance notice saying, "May the present summary [enlist] the co-operation of universities and their patrons, professors and their students, in a work that promises results so important to human welfare" (Abbe 1890b).

Before Abbe's *Second Collection* appeared events overtook the weather organization. A few years after the Allison Commission hearings, Congress in 1891 transferred the weather service into the Department of Agriculture. That action postponed any possible movement toward numerical forecasting. The Secretary of Agriculture Jeremiah Rusk brought in astronomer and meteorologist Mark Harrington from the University of Michigan as director of the new U.S. Weather Bureau. At a time when many thought that climate had a direct bearing on health, Harrington "placed major emphasis on climate studies." Later on, however, Harrington called for a meteorologist who could "lift the art of weather forecasting from its present ptolemaic stage into the stage of true theory . . . ." (Harrington 1895). Meanwhile, Rusk's successor, J. Sterling Morton, in 1893 investigated Harrington's alleged mismanagement, further diverting the director's attention from innovative theoretical research (Whitnah 1961). Morton also attacked Abbe. Morton had taken office with the Cleveland administration just before the Panic of 1893 and the ensuing depression. Budget cutting extended across all agencies. He let it be known that over 20 years Abbe had received $90,000 in compensation "for which the government had received back no adequate return." Morton demoted Abbe and reduced his salary, notifying him in writing that he had never earned it anyway (Abbe 1955). Abbe's record of accomplishments and great diligence clearly belied that judgment, and

Harrington defended Abbe. By then Abbe no longer directed meteorological operations or research. In the new Weather Bureau he continued to edit *MWR* and to advance his thinking on mathematically based approaches to forecasting. Both Willis Moore and Charles Marvin, subsequent directors of the Weather Bureau, considered proven empirical methodology to be adequate to the task (Nebeker 1995).

Abbe soldiered on. He continued translating, and in 1893 his *Second Collection* appeared (Abbe 1893a). The selection and focus of these articles reveal an advance in the field and in Abbe's own thinking since his *First Collection*. The central message here signaled the scientific community's growing realization that cyclones did not represent closed systems, but resulted from larger-scale circulation processes, in short, a three-dimensional fluid dynamical problem.

Abbe's *Third Collection* contains mostly papers published prior to 1904, preceding important articles by Bjerknes (Abbe 1910). He incorporated papers on the effect of the Earth's rotation on the motions of the atmosphere and on thermodynamics. He included articles on the theory of cyclones and on balloon measurements of the upper air. These papers describe rapidly advancing European ideas with respect to the theory of cyclones. He looked ahead:

> "the two memoirs by Margules . . . introduce us to the great problems of the future, that is, the thermal transformations of energy persistently going on in the atmosphere . . . . *It only remains for future students to combine the equations of thermodynamics with those of hydrodynamics . . . that we may hope will eventually be attained by the analysis of fields of force that is now being perfected by Bjerknes of Christiania.*" [italics added] (Abbe 1910).

What motivated Abbe's selection of the papers in the three collections? One might infer that his expressed view drove the choices; "meteorology can only be advanced . . . by the devotion to it of the highest talent in mathematical and experimental physics . . ." (Abbe 1893a). The papers he selected represented the best efforts of theoretical physicists at the time to describe motions of the atmosphere as a whole in mathematical terms. And for many years the three collections provided the only concentrated examination of dynamic meteorology.

ABBE'S 1901 PAPER: "THE PHYSICAL BASIS OF LONG-RANGE WEATHER FORECASTS." After nearly 30 years of pondering the subject Abbe in 1901 published his theoretical synthesis (Abbe 1901). The article, first delivered that year at the AAAS in Denver, Colorado, carried the exposition well beyond the earlier work by Ferrel. Abbe's article proved to be remarkable first for its scientific vision, and second because almost no one since has cited it. Saltzman (1967), in turn cited by Nebeker (1995), is an exception. By contrast, three years later, Bjerknes made essentially the same case in an article widely acclaimed as ushering in a new era in meteorology (Bjerknes 1904). He wrote without citing Abbe. The two papers merit comparison. First, their similarities are as follows: Abbe's focus expressed in his title "The physical basis of long-range weather forecasts" closely resembles Bjerknes' title, "The problem of weather prediction, treated from the standpoint of mechanics and physics." Both cataloged the necessary equations of state, continuity, thermodynamics, and motion. Both recognized that the equations of motion, not the thermodynamic equations, posed the greater challenge. Both recognized the need for upper-atmospheric observations.

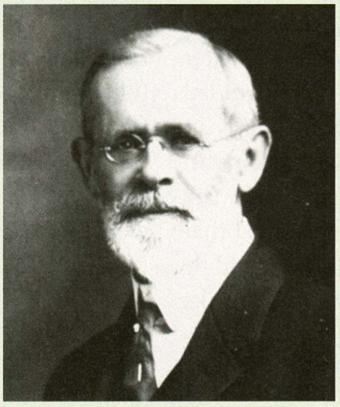
The papers differ substantially in four ways. First, Abbe recognized more fully the extreme technical challenge posed by initializing the equations of motion with observations. Bjerknes, writing three years later, blandly and prematurely claimed to have at hand the technical means for handling the equations. This variance in perspectives may have derived in part from the success of the Wright brothers, leading Bjerknes to anticipate substantially more accessible upper-air data (Nebeker 1995). Second, the papers differed in their consideration of approaches to solving the equations. Abbe provided far more detail. He explicitly displayed the basic equations; he wrote discursively, giving considerable background for each equation; he explored the expansion of the solutions in terms of spherical harmonics; he considered geometric, graphical, and numerical techniques as well; he pointed out that "a full knowledge of the actual physical conditions at any initial moment is not now practically obtainable . . . ." Previous efforts at solving the problem of the general circulation had been oversimplified, assuming a dry and cloudless Earth, thus fatally separating the thermodynamic from the hydrodynamic aspects of the problem.

Abbe argued that earlier authors offered oversimplified, idealized representations of actual atmospheric conditions that did not apply to long-range forecasting. He emphasized that one cannot merely examine weather charts empirically, but must attack the problem "analytically and algebraically" in order to devise "auxiliary geometrical and graphical methods" of solution. He considered the complexity of analyzing atmospheric conditions as posing problems that are the "most difficult of solution of [any] in science." Abbe insisted that before completely solving the equations of motion for the atmosphere, one must develop general theorems embodying essentially correct ideas about atmospheric mechanics. He then discussed at length the lack of stationarity in atmospheric flows, providing theoretical support for this observed feature of atmospheric circulation. He also noted the need for upper-atmospheric data. Bjerknes wrote more tersely. He focused attention primarily on solving the equations numerically. He suggested an approach similar to those that have subsequently evolved, but he treated the subject in a sketchy and general manner. In fact, at that time, neither Abbe nor Bjerknes "saw a way to make mathematical weather forecasting a reality" (Gedzelman 1994).

Third, Abbe emphasized long-term forecasting. His years of work as an operational forecaster, and his experience with minimally trained weather observers, convinced him that the daily forecast (or even the two- to three-day forecast) might best be pursued using an empirical approach, especially given the computational limitations of the time. Bjerknes, however, with less practical experience, emphasized short-term forecasts of a few days, employing numerical computation. Abbe, on the other hand, considered dynamical equations as tools for forecasting the weather over a period of weeks, months, or even an entire season, which in essence is a climatological or seasonal forecast. Abbe suggested the desirability of knowing whether the season would be especially sunny or rainy or whether it would bring considerable "severe freezing weather." What a breathtaking

CLEVELAND ABBE (1838–1916)

Abbe grew up in New York City, in a prosperous merchant family descended from New England Puritans. He graduated in 1857 from the Free Academy (now City College) where he excelled in mathematics and chemistry. Thereafter, for two years he taught engineering at Michigan State University and studied astronomy with Franz Brünnow at the University of Michigan. When the Civil War broke out he attempted to enlist in the Union Army, but failed the vision test. During the war years he worked in Cambridge, Massachusetts, as an assistant to Benjamin Gould, who was an astronomer and head of the longitude department of the U.S. Coast Survey. There he developed an interest in postgraduate study abroad and sought a position in Russia. Otto Struve, director of the Nicholas Central Observatory at Pulkovo, near St. Petersburg, invited him to serve as a supernumerary astronomer. Abbe arrived there early in 1865. Struve set him to reducing the astronomical observations made in the eighteenth century by Astronomer Royal James Bradley in Greenwich, England. While at Pulkovo he acquired fluency in German, the working language of the observatory staff. His exposure to the German culture and scientific methodology left him well prepared and enthusiastic for a career in astronomy.



After two years at Pulkovo Abbe returned home. In May 1867 Simon Newcomb at the Naval Observatory in Washington hired him to make computations for the *Nautical Almanac*. Through an acquaintance, whom he met aboard the ship on his return from Europe, he learned of an opening for director at the Cincinnati Observatory. He realized his fervent goal when the Cincinnati Astronomical Society hired him to begin work in June 1868. Eager to excel, Abbe drew up a far-reaching plan for a full program of astronomical endeavor, reflecting his experience at Pulkovo. Unfortunately, the organization lacked funding. He reacted optimistically, remembering that meteorological conditions directly affect the work of astronomers. He won approval to report on and predict the weather, which would satisfy scientific interest and benefit the public. Weather forecasts could be generated at a minimal expense and perhaps produce income. Thus, Abbe made the career change that determined the rest of his professional life.

Abbe and the observatory board got short-term funding from the Cincinnati Chamber of Commerce. He enlisted 20 volunteer weather observers to report conditions. Western Union agreed to permit his observers to communicate without charge. Those arrangements enabled Abbe to commence forecasting the weather on 1 September 1869. Unfortunately, the funding ran out and forecasts ceased in June 1870. Lacking further budget commitments, Abbe returned to New York. Nonetheless, he had demonstrated the viability of weather forecasting using available technology. Thus experienced, he was ready when Congress mandated the formation of a national storm warning system. He interviewed in Washington and joined the government as its chief meteorologist in January 1871. He remained with the weather service for the next 45 years.

In 1912 the Royal Meteorological Society presented Abbe with the Symons Memorial Gold Medal, citing his contribution "to instrumental, statistical, dynamical, and thermodynamical meteorology and forecasting." Upon Abbe's death in 1916, Ernest Gold in London wrote, "To us in Europe he was the most outstanding figure in American meteorology since Ferrel and there is no student of the dynamics of the atmosphere who is not under a great debt to him."

vision for 1901! He rightly concluded "we must not expect to realize these hopes in this generation." And so, at the dawn of the twentieth century, Abbe clearly recognized the three dimensions to the work of meteorologists: forecasting, climatology, and physical theory. He wove them tightly together throughout the fabric of the paper, reflecting his accumulated, evolving, enriched perspective of the previous 30 years, and he grounded the article solidly in the mathematical and physical fundamentals, while at the same time realizing the mathematical difficulties.

Finally, Abbe's emphasis on long-range forecasting led him to a separate global vision in this paper, a view not even mentioned by Bjerknes in 1904: the notion that regional climate variations propagated their effects worldwide. This arose from Abbe's empirical study of droughts and famine in India in 1896 and 1899, which were the worst in his view since 1769. He recognized that one could attribute these droughts and associated crop failures not only to conditions in Tibet, but also to the southeast trade winds of the Indian Ocean, because they both affected the monsoons. He pointed out that the equator does not divide the Earth into "symmetrical systems of wind in the northern and southern hemispheres." He then proclaimed a most important insight resulting from this "radical" view of the "general circulation of the atmosphere": conditions in the southern Indian Ocean in March affect India four months later and Japan six months later. Those conditions may affect central Africa or Australia during the entire winter season in the Southern Hemisphere. He concluded that the "great disturbance that starts annually in the Orient" affects North America and Europe in one to three years. Much of the discussion in the paper makes it clear that Abbe then envisioned that this evolution of seasonal weather patterns could be predicted by theoretical analysis. Thus, Abbe ranks among the first to recognize the global consequences of what came to be known decades later as the *El Niño* phenomenon (Walker 1924).

Significantly, Abbe did not view or treat Bjerknes as a competitor, but as precisely the kind of young scholar he hoped to attract to meteorology. Abbe appreciated that Bjerknes' circulation theorem simplified the mathematics in many situations of interest (Abbe 1911). Abbe's relationship with Bjerknes underscores this assessment, and squares with his mission to promote the greater good. He solicited an article from Bjerknes for *MWR*, and shared upper-air data with him. He welcomed Bjerknes to the United States in 1905, and arranged speaking engagements for him in Baltimore, Maryland, and Washington, where he could expound his views on atmospheric prediction as a problem in physics. On that occasion, Abbe introduced Bjerknes to Robert S. Woodward, astronomer–mathematician and president of the Carnegie Institution of Washington. Woodward later funded a full-time assistant for Bjerknes, thus helping launch "the father of modern meteorology" on a stellar career (Friedman 1989). This typified Abbe's self-effacing style and "his never-failing willingness to help everyone who came to him for information or advice . . ." (Humphreys 1919). In this way, Abbe played his part as a facilitator, not merely promoting the meteorological community across continents, but across generations.

CONCLUSIONS. For most of 30 years Cleveland Abbe served as initiator, scientific watchdog, and theorizer at the Weather Bureau. He set a masterful example from his forecasting methodology to his professional standards, his voracious reading habits, and his voluminous correspondence with other scientists. Men at headquarters remembered that Abbe made the rounds every day and almost always threw down a new intellectual challenge. In this period he had an impact on the weather service of the United States equal to or greater than that which any of his European contemporaries had on their meteorological services. His monumental effort to translate and publish articles key to dynamic meteorology accelerated and aided international progress toward introducing theoretical principles into the forecasting process. His remarkable paper of 1901 drew together the theory and the mathematics necessary for numerical forecasting. Friedman (1989) attributes to Bjerknes the vision of meteorology as a problem in physics. For close to 30 years prior to Bjerknes' work, however, Abbe understood and propounded the necessity of applying physical laws to the analysis of atmospheric data. Kutzbach (1979) singles out the thermal theory of cyclones as the key scientific advance of this period. Abbe continuously contributed to international scientific dialog on that concept. Nebeker (1995) postulates as the most important meteorological achievement of the twentieth century the integration of the three dimensions of climatology, forecasting, and theoretical meteorology. Abbe comprehended that intersection well before it became fashionable. From a twenty-first-century vantage point his 1901 paper seems thoughtful and prescient. At his best Abbe stood tall among the pioneers of meteorological science. In simple fact, for these 30 years Abbe marched at the vanguard of the development of modern meteorology as theorizer, integrator, facilitator, and public servant.

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