

Weather by the Numbers

The Genesis of Modern Meteorology

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1 :: A Stagnant Atmosphere: The Weather Services before World War II

The meteorological “renaissance” that began in Norway and spread to other European countries at the close of World War I did not extend to the United States. In Europe, meteorology held the same “rank” as astronomy in academic institutions, and research on its theoretical underpinnings was carried out at several academic institutions in Norway, Germany, and England. But in the United States, the top academic institutions did not treat meteorology as a topic on a par with any physical science. If offered, meteorology was typically found in geography courses covering climate. At state universities, meteorology courses were often related to agricultural instruction and developed by Weather Bureau personnel assigned to conduct state climatological and crop studies.¹

The desultory status of meteorology in the United States, where other branches of the earth sciences began growing rapidly in the first part of the twentieth century, was particularly pronounced. Academic geophysics benefited from new philanthropic support. In 1905, the newly founded Carnegie Institution in Washington launched its new Geophysical Laboratory to “take possession of the vacant ground between geology and physics and geology and chemistry,” and its \$2 million endowment soon made it an international leader in petrological studies.² In 1909 the Carnegie Institution’s Division of Terrestrial Magnetism, boldly declaring its intention to map the geomagnetic field of the entire earth, commissioned the non-metallic ocean-going ship *Carnegie* to undertake this survey. A subsequent Carnegie Institution grant established the Seismological Laboratory at the nascent California Institute of Technology in 1921, and that same year the eminent physicist Robert Andrews Millikan was named Chairman of the Executive Council of Caltech.³ By that time, the Rockefeller Foundation’s General Education Board also was supporting research in academic geophysics, offering a grant to Harvard University to support experimental physicist Percy Bridgman’s studies of high-pressure on materials. The appointment of Norwegian oceanographer Harald Sverdrup as

director of the Scripps Institution of Oceanography in 1936 signaled its rise as a leading research center in physical oceanography.⁴ Though as late as 1940 no US university offered a curriculum in all the component fields of geophysics recognized by the American Geophysical Union (and critics decried the absence of rigorous mathematics, physics, and chemistry training in most university geology programs), research and PhD production in many fields of geophysics, apart from meteorology, were robust before World War II.⁵ Funding remained inadequate for US government agencies involved in geophysics and the earth sciences: for instance, the superintendent of the US Coast and Geodetic Survey complained in 1921 that the salaries for its employees were “below those paid for skilled labor in mechanical trades outside the US government.” But the Coast and Geodetic Survey faced fewer challenges in meeting its mission than did government meteorologists.⁶ Expanding opportunities for research in other earth sciences fields thus made the contrast with meteorology stronger still.

Meteorological research in the United States was limited because meteorology fell under the purview of the Weather Bureau, which in turn operated under the jurisdiction of the Department of Agriculture. Although the Weather Bureau—headquartered in Washington, DC (figure 1.1)—had a mission to keep the general public informed of upcoming weather conditions, its primary obligation was to provide agricultural forecasts. Because it was a government agency, any research it performed had to produce an immediate practical result.⁷ Similarly, the other two very small “weather services” in the country—maintained by the War Department and the Navy Department—existed to provide specialized forecasts for Army and Navy units. Any research they conducted supported operational requirements.

Military use of aviation increased dramatically during the Great War, and with it the importance of meteorology in keeping pilots and aircraft safe. The Weather Bureau received a special appropriation of \$100,000 to establish aerological stations and coordinate services with the War Department and the Navy Department once the United States entered the war, and “flying-weather forecasts” for the military and postal service began in December 1918. Although aviation funding continued after the war, the Weather Bureau made little progress in expanding its services during the immediate postwar period. In contrast, European governments were heavily subsidizing the establishment of civil airways and the meteorological services that supported them.⁸ As Secretary Charles F. Brooks of the American Meteorological Society (AMS) noted in 1922, the Belgians were “astonished” that the Weather Bureau’s annual budget was only \$2 million—or two cents per US resident—and he concluded that “meteorological expenditures and general

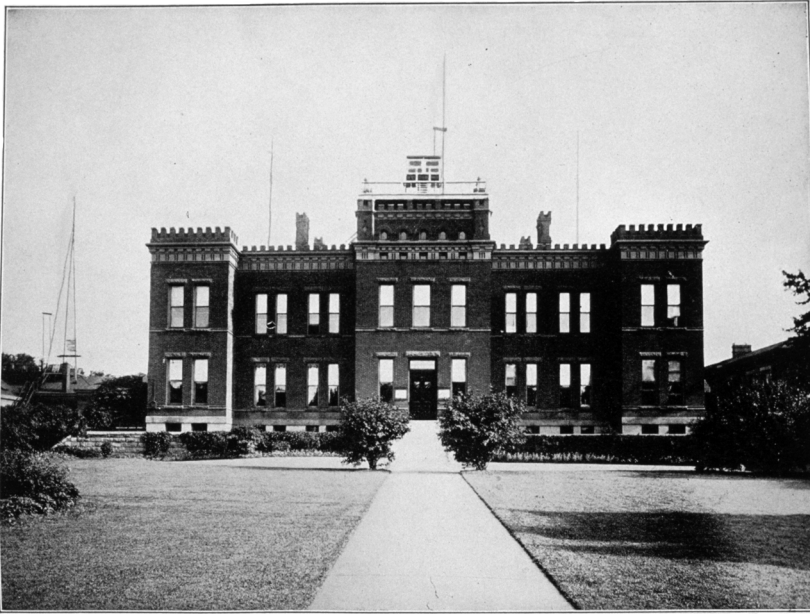


Figure 1.1

US Weather Bureau Building, Washington, circa 1912. (NOAA National Weather Service Collection, courtesy of NOAA Central Library)

interest in meteorology are greater in Europe than in the United States.”⁹ Because of the superior financial support, atmospheric studies in Europe were aided by both academic and applied meteorologists.

While meteorology flourished in Europe after World War I, it stagnated in the United States. The initial promise of increased funding, the rise of aeronautics, and the demand for meteorologists that emerged during the war years, very quickly gave way to retrenchment. Progress was limited—academically, theoretically, and within the applied sector. Underfunded, undermanned, undertrained, and chronically discouraged Weather Bureau personnel advanced the practical, forecasting side of meteorology, despite being crippled by externally imposed limitations. With demobilization, the Army Signal Service and the Navy’s weather services struggled to provide weather forecasts with wartime leftovers who saw potential career opportunities in flight forecasting for military pilots. And while the Signal Service concentrated on designing and building new meteorological instruments, it was the Navy that actively sought a more theoretical path toward weather forecasting. The Navy’s drive to professionalize its ranks would lead to the

first graduate meteorology program in the United States. And by the late 1930s, major meteorology programs would be established at MIT, at NYU, and at Caltech. These programs, and others that followed, would lay the groundwork for US meteorology during World War II and the Cold War. This educational foundation was a necessary condition for numerical weather prediction efforts that would begin immediately after World War II.

Weather for All Reasons: The Weather Bureau

The US Weather Bureau became the nation's official weather service in 1891. However, a weather observation network had been in place since the early nineteenth century, when the US Army Medical Department, academics in New England and New York, and the General Land Office began systematically collecting data. By the 1840s, observations had expanded beyond basic temperature, pressure, and precipitation readings to include data on storms and winds. Between 1849 and 1861, the Smithsonian Institution was home to meteorological research, which was directed by the institution's first secretary, Joseph Henry. The Smithsonian Meteorological Project, focusing on storm movement and climate statistics, was undertaken with several federal agencies as well as the Canadian government. In 1870, the US Army Signal Office began telegraphing daily reports of current conditions and forecasts (called "probabilities"), and the Signal Office continued to function as the national meteorological service until 1 July 1891. An act of Congress dated 1 October 1890 (26 Statutes at Large, 653) then transferred weather duties to the Weather Bureau under the Department of Agriculture. The Weather Bureau's functions, as set forth in section 3 of the act, were as follows:

The Chief of the Weather Bureau, under the direction of the Secretary of Agriculture, shall have charge of forecasting the weather; the issue of storm warnings; the display of weather and flood signals for the benefit of agriculture, commerce and navigation; the gauging and reporting of rivers; the maintenance and operation of seacoast telegraph lines and the collection and transmission of marine intelligence for the benefit of commerce and navigation; the reporting of temperature and rainfall conditions for the cotton interests; the display of frost, cold-wave, and other signals; the distribution of meteorological information in the interest of agriculture and commerce and the taking of such meteorological observations as may be necessary to establish and record the climatic conditions of the United States, or are essential for the proper execution of the foregoing duties.¹⁰

Sixteen divisions within the bureau carried out its mission. Some were administrative (stations and accounts, supplies, printing, telegraph, library); the remainder covered the range of relevant scientific interests—meteorology,

hydrology, seismology, volcanology—and the instrument division that supported them.

Across the nation, five regional districts issued forecasts and warnings. The eastern region's office was within the Weather Bureau's headquarters in Washington, and its chief forecaster could veto forecasts issued by the other regions. The eastern region's office also issued the daily weather maps (figure 1.2). The district offices were, in turn, supported by more than 200 regular stations (figure 1.3), each employing between one and fifteen full-time paid employees who took and transmitted observations and issued local area forecasts. If these employees had time, they performed supervisory functions and conducted limited research. Repair stations and vessel reporting stations also had full-time paid staffs. Additionally, nominally paid (\$10–\$25 per month) employees made specific observations (for example, by reading river gauges). Since these stations could not adequately cover the nation, several thousand unpaid volunteers maintained “cooperative stations” and collected data for climatological studies and for crop and road services. These volunteers often distributed forecasts and warnings in their local area.¹¹

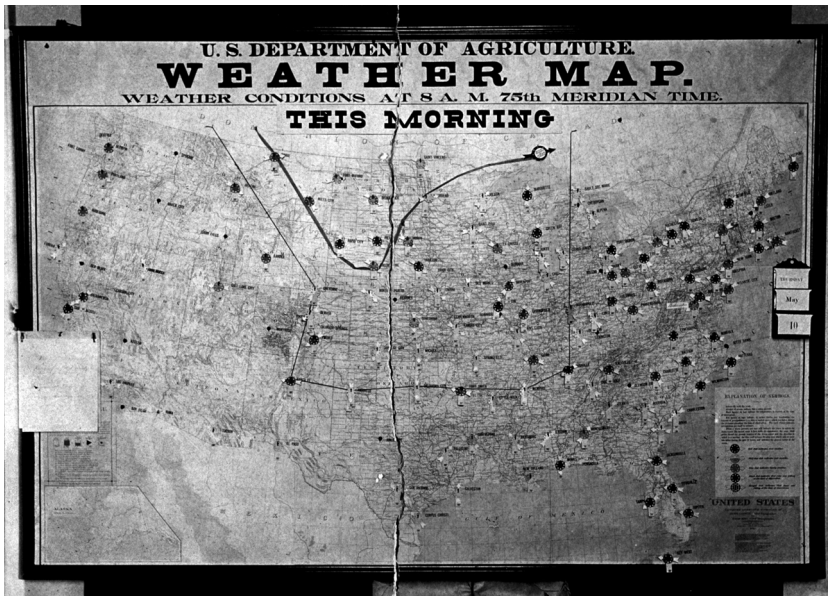


Figure 1.2

Weather Bureau weather map, circa 1900. (NOAA National Weather Service Collection, courtesy of NOAA Central Library)

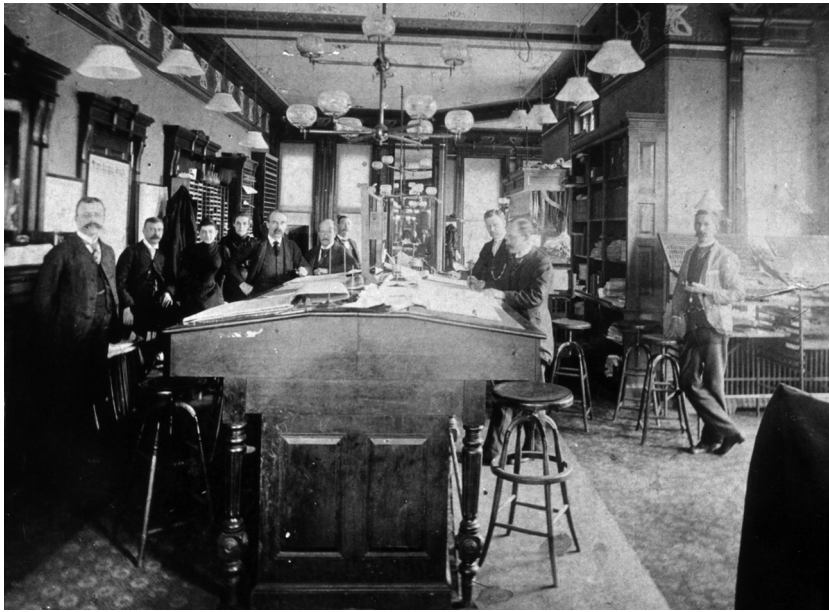


Figure 1.3

Unknown Weather Bureau office, circa 1900. (NOAA National Weather Service Collection, courtesy of NOAA Central Library)

Paid or volunteer, Weather Bureau personnel were dedicated to providing the best possible weather forecasts to a wide variety of agricultural, commercial, and industrial interests. Although many people thought the recently inaugurated (1919) and highly publicized aviation service occupied the bulk of the bureau's time, in fact it was a minor, albeit growing, portion of the workload.¹² Furthermore, since many citizens were involved, directly or indirectly, with agriculture, it is easy to understand why many people thought the Weather Bureau provided services just to them.

By the early 1920s, the Weather Bureau's five regional offices produced weather maps and written forecasts for the general public, and transmitted them to major media outlets. Newspapers in larger communities printed the forecasts that were also posted in a variety of public places: railroad stations, post offices, hotels, and department stores. The bureau was *the* source for weather information. Local stations issued forecasts and severe weather warnings for a 20-mile radius.¹³

The Weather Bureau also performed extensive work in agricultural meteorology. Although most forecasts and advisories were tailored to a single crop,

the weekly *National Weather and Crop Bulletin* presented the previous week's meteorological data and the weather's effect on vegetation, stock, and farm work. The bureau collected specialized data for corn, wheat, cotton, sugar, and rice states. (Cattle-grazing states pushed hard for similarly tailored information.) It published data on fruit frost for tobacco, fruit, truck, and alfalfa seed districts. Fruit-frost warnings were important to citrus growers in California and to orchardists in Oregon and Washington—such warnings enabled them to heat their orchards by burning oil in smudge pots and thereby save their crops from a hard freeze. Similar forecasts and advisories were aimed at tobacco and grain farmers, at New York apple growers (who needed to spray for scab), at millers (who needed to rid their mills of Mediterranean flour moths by flooding them with very cold air), and at beekeepers (whose bees needed a cleansing flight). Western foresters lobbied hard for expansion of fire-weather forecasting, which used meteorological conditions to warn of extreme fire danger and to advise when precipitation would help to quench fires. Additional appropriated funds, in combination with private funding, helped to develop and extend more detailed warnings in fire-sensitive areas.¹⁴

The Weather Bureau's routine use of probabilities for agricultural and more general forecasts for the public led to a widely held assumption that meteorology was more statistical than geophysical. For example, environmental historian Stephen J. Pyne later argued that meteorology is "a statistical science" because it deals with large-scale events. He further declared that fire had "helped to bring meteorology out of the clouds and back to the earth."¹⁵ However, both assessments are incorrect. Although statistical methods were used to draw information from long-term climatological trends and to develop forecast probabilities (e.g., a 50 percent chance of rain), meteorology was and is fundamentally a geophysical science. Furthermore, the field forecasters—the ones providing fire-weather forecasts—have always been "down to earth." Forecast centers, at least in the United States during the first half of the twentieth century, had no time for theoretical flights of fancy.

Supporting commerce, Weather Bureau forecasters advised shippers when extreme temperatures might harm produce and animals in shipment. For example, freezing temperatures could ruin bananas in transit, and extreme heat could kill livestock en route from farms and ranches to feedlots and slaughterhouses. As Chicago Weather Bureau "official forecaster" Henry J. Cox wrote for *The American Magazine*, "the weather has a finger, so to speak, in almost every business pie." Cox emphasized that businesses dealing in perishable crops and livestock would do well to consult the weather map or call their local forecast office for advice. Doing so saved businesses millions

of dollars every year. If it were not for the Weather Bureau, Cox continued, consumers “would have to pay more for [their] fruit and vegetables.”¹⁶ These free weather forecasts saved businessmen and their customers millions of dollars annually—many times the bureau’s budget.¹⁷

The Weather Bureau also created “highway forecasts,” which had been demanded by automobile associations and by road commissioners who needed to know when to activate snowplows during the winter. Marine forecasting also fell to the Weather Bureau, which in 1904 assumed this responsibility from the Navy. Cooperative agreements with ocean shippers, including the fleets of Standard Oil and the Texas Company, enabled the bureau to receive timely observations from ocean areas, which assisted forecasters making predictions for these same units.¹⁸

Not all of the Weather Bureau’s tasks were meteorological. Utilities and businesses that used fresh water encouraged the bureau to expand river and flood services. Flood warning systems were adequate, but precipitation-related streamflow measurements remained underfunded—a significant deficiency during the great drought of the early 1930s. Additionally, the bureau began collecting and publishing earthquake data in 1914 and monitored volcanic activity—especially on Hawaii.¹⁹ Although the latter task was eventually passed to the US Geological Survey, the Weather Bureau was apparently viewed as an all-purpose collector of earth science data, weather-related or not.

The fastest-growing forecasting and data-collection effort during the inter-war period supported aviation. Aeronautics—airships, balloons, and fixed-wing aircraft—had taken on greater importance because of World War I. At war’s end, military meteorological organizations that had expanded to fill the need rapidly contracted. However, the aviation assets remained, and safe flight required accurate forecasts of take-off, in-flight, and landing conditions. The unmanned military services could not provide the forecasts, and increasing numbers of air mail flights also required weather information, so in July 1919 the bureau started its flying weather forecasting service for the Army Air Service, the Navy, and the Postal Service. Shortly thereafter, commercial aviation companies began requesting forecasts. Aviators also made more frequent pre-flight visits to weather stations.

That pilots wanted forecasts was good news. But forecasters did not have sufficient upper-air observations and local surface observations to provide them with useful weather information. Demand increased annually as larger numbers of pilots requested forecasts and other specific weather information. The Weather Bureau negotiated cooperative agreements with both the Army Air Service and the Navy. Air Service pilots began visiting stations to obtain weather information and to make contacts with supporting meteorologists,

and the Weather Bureau initiated a lecture program that touched on climatology, air currents, physics of the air, and other aviation-related meteorological topics. Additionally, a Navy meteorologist had a desk at the Weather Bureau's headquarters office so he could prepare a weather map with his counterparts there before transmitting it to naval installations throughout the nation. The Army and the Navy shared the cost of obtaining upper-air data by forwarding their pilot-balloon (PIBAL) reports to Weather Bureau headquarters. The (usually) red basketball-sized pilot balloons, filled with hydrogen gas, were sent aloft and rose at a predetermined rate. (At night, observers hung a small paper lantern containing a lighted candle well below the balloon so they could track it in the dark.) Observers tracking the balloon could then determine winds aloft near the station. Kites also carried meteorological instruments that recorded upper-air information (figure 1.4).²⁰

The rapid growth in aviation after World War I had a huge impact on the Weather Bureau. By the early 1930s, the United States had 25,000 miles of civil airways for which the bureau provided support, relying on more than 500 cooperative (volunteer) and second-order (minimal pay) stations along the routes. The 13,000 miles of airways that supported all-day flying were served by 24-hour stations. These were significantly more expensive to operate than stations providing routine weather services to agriculture and the public.²¹

Responding to yet other constituencies, the Weather Bureau also began providing climatological data. More than 4,500 volunteers ("cooperative observers") made observations and mailed them monthly to headquarters. The climatology section compiled the data, determined average temperatures and precipitation, and published the results.²²

During the interwar period, the US insurance industry expanded its product line from life and fire coverage into weather insurance and became a major consumer of climatological data. As this insurance sector grew, so too did the demands on the Weather Bureau for another "free" product. Anyone could ask for—and receive at no charge—climatology data destined for publication. Rainfall data that would not otherwise have been computed could be ordered at a cost of 70 cents an hour in overtime pay.²³ Demand for rain and hail insurance increased dramatically in the 1910s. In New York, Henry W. Ives and Company issued "Pluvius Weather Policies" that insured against losses due to unfavorable weather: crop destruction, penalties due to construction delays, and gate receipts from washed-out sporting events. Customers had to purchase the policy at least a week in advance of the insured event. Why a week? Because weather forecasts were good only for about 24–36 hours. No one could predict the weather a week in advance. Companies based premiums on climatological data. Premiums were higher, for example, if rain

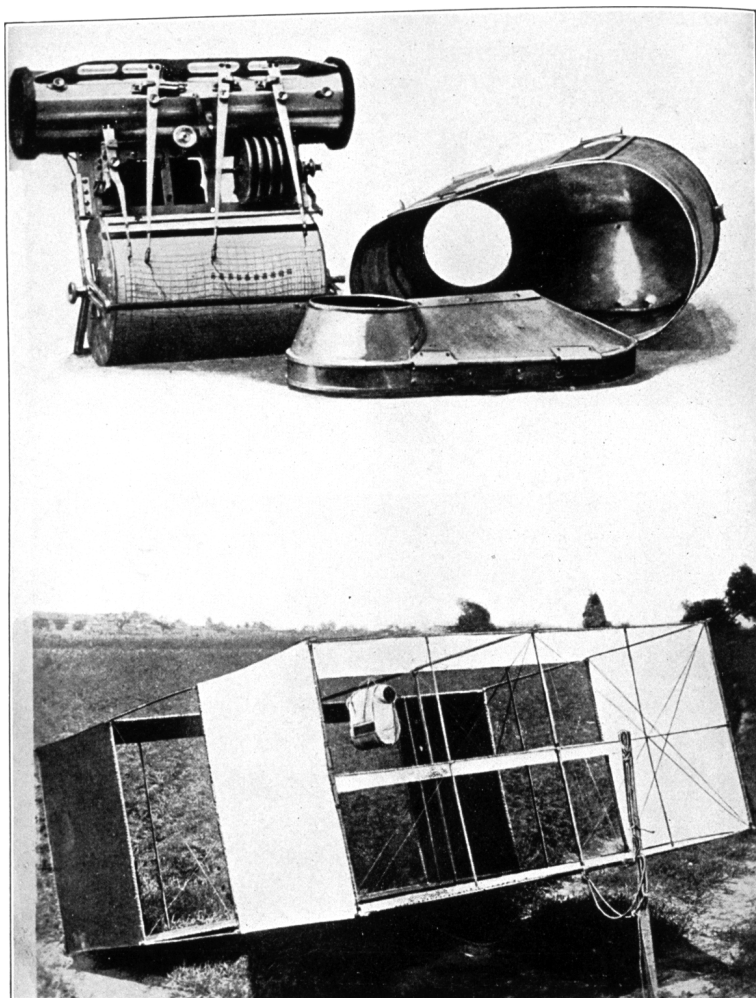


Figure 1.4

"Kite equipped for meteorological observations," circa 1912. (NOAA National Weather Service Collection, courtesy of NOAA Central Library)

was more likely than dry weather on the day of a sporting event. In 1919, customers spent \$30 million on premiums covering \$500 million in risk.²⁴ Yet for the climatology data to determine this risk, the insurance companies paid next to nothing.

The Weather Bureau had a clearly defined civil role, but during wartime it also supported military operations. During World War I it provided weather forecasts and observations (surface and upper air) in support of aviators, balloonists, and artillery units. Two members of the Weather Bureau staff took on reserve status in the Army Signal Service and worked with others from the bureau who, along with their British and French counterparts, had joined the active-duty forces to form a special forecasting unit in Europe. In addition to aviation, as detailed below, their forecasting duties included predicting winds for gas dispersal and ballistics.²⁵

On the home front, the Weather Bureau provided forecasts and warnings to Army camps and Navy bases, and forecasts to railroads handling food and supplies. The bureau also provided meteorological instruments to the military services and climatological data to the Surgeon General's office, studied upper-air conditions for aviation, reported vessels entering and leaving ports where they had stations, and assisted in organizing gas and flame regiments.²⁶



After the armistice of November 1918, the question arose of which agency would continue to provide weather services to military activities. President Woodrow Wilson convened a special board that heard arguments in support of and in opposition to separate military meteorology services. The Weather Bureau's leaders vehemently opposed any suggestion that it should not provide all of the nation's weather services. While acknowledging the necessity of maintaining a small number of trained personnel serving meteorological units at flying fields, naval bases, and ordnance proving grounds, the bureau argued that the United States had too few qualified meteorologists to spread them among several agencies. With 90 percent of the "trained and dependable" meteorologists in or associated with the Weather Bureau, its leaders argued that in the event of another war the US government should do what the Coast Guard had done during World War I: make Weather Bureau personnel members of the military services.²⁷ The provision of weather services was an ongoing point of discussion that extended through World War II and into the Cold War era as the government sought to eliminate duplication of services.

The impoverished Weather Bureau, already stretched thin just trying to meet the myriad demands of its non-paying customers, was not in a position

to pursue a research agenda. In contrast, many Department of Agriculture agencies devoted considerable time, talent, and funding to research. While 18 percent of the budget of the Bureau of Chemistry and Soils and almost half of the budget of the Bureau of Experiment Stations were earmarked for research, the Weather Bureau's budget included *no* research funds.²⁸ Weather Bureau appropriations covered routine weather services for the public, for agriculture, and for industries. Research efforts came last, if at all.

Weather Bureau meteorologists were interested in advancing their discipline, but their "investigations" did not usually extend to asking or answering theoretical questions. Investigations focused instead on the relationship between weather and crops, on storm development, on upper-air conditions, on climatology, on how solar radiation affected weather and climate, and on the improvement of meteorological instruments. With the government's emphasis on practical value, Congress was not going to appropriate funds for research not expected to yield economically important results.²⁹

Research in agricultural meteorology did include researching the effects of temperature, precipitation, and other elements of weather. Winter wheat is affected by ambient air temperature and by whether precipitation falls as snow or as rain. Determining optimum weather conditions helped farmers anticipate bumper crops or poor harvests. The Weather Bureau continued conducting research on the impact of certain weather conditions on harvests and on the geographical distribution of farm products.³⁰

Another Weather Bureau study, one that was important to civil engineers, examined sky brightness—that is, the amount of expected natural lighting during the seasons, at various hours of the day, and under various atmospheric conditions. When designing and constructing buildings, engineers had to make allowance for natural illumination. Although it was beyond the scope of their studies, bureau meteorologists recognized a need to determine and add the amount of light being reflected from surrounding buildings.³¹

Investigations of solar radiation, which became routine in the early 1920s and extended throughout the interwar period, soon embroiled the Weather Bureau in a very public controversy with non-meteorologists. (By "non-meteorologists" I mean scientists who were not engaged in studies of atmospheric physics, not physicists and other researchers who were devoting attention to the atmosphere and to the broader field of geophysics.) This would not be the first or the only time that scientists without a meteorological background would attempt to tell the meteorology community in general and the Weather Bureau in particular what physical variables were really important in understanding the atmosphere.

Scientists both within and outside the Weather Bureau were attempting to determine whether there was a link between solar intensity and weather phenomena that would aid forecasting. Investigating solar radiation involved making continuous records of the amount of radiation received on a horizontal surface to determine the heating rate during the day, the amount of heat lost during the night, and the relationship between these values and atmospheric conditions. Early on, Weather Bureau researchers were not as optimistic as those who argued that observed solar intensity was an accurate indicator of incoming weather, although they did allow that there might be a connection between solar intensity and variations of the weather over many years. Although the Weather Bureau acknowledged that solar radiation was important to weather, it did not believe that insolation (incoming solar radiation) varied greatly from day to day. The variations were so small that measurable meteorological effects were in doubt.³²

Vigorously and publicly opposing this view was Charles Greely Abbot, Assistant Secretary of the Smithsonian Institution. Abbot, trained in chemistry and physics at MIT, was the second director of the Smithsonian's Astrophysical Observatory. He was convinced that even small changes in the sun's heat could significantly affect earth's weather. By correlating solar output with weather conditions over a period of several years, Abbot became convinced that it would be possible to use measurements of solar radiation alone to predict the weather—and not just for the next day or so, but for weeks, months, or years in advance. Obtaining accurate measurements was the primary difficulty because, according to Abbot, a change of 1 percent in solar radiation received at the earth's surface could produce noticeable weather effects. Therefore, measurement stations were moved from the United States to an observatory in Chile's Nitrate Desert, a place of clear skies and little rainfall. (Another station was established later on Mount Harqua Hala in arid Arizona.) Abbot argued that, whereas the recorded change in solar radiation and weather might be small at the Chilean station because the affected ground area was so large, the same radiation could produce huge changes toward the poles. Therefore, it was not necessary to measure the insolation at the site of the forecasted change—one only needed to get an accurate measurement at a few optimally placed stations.³³

Senior personnel at the Weather Bureau, particularly Chief Charles F. Marvin, disagreed vehemently. Disputing Abbot's claims, Marvin (an instrument specialist) argued that Abbot's observed "variations" in solar radiation measurements were not necessarily due to changes in the sun's output. Since the measurements were taken after the sun's rays had passed through 20 miles of earth's atmosphere, it seemed more likely to him that radiation variability

depended on the state of the atmosphere and not on solar variability. Abbot countered that it made no difference whether the changes were on “the sun, the earth, or some distant star” if they enabled weather prediction.³⁴ Although a reluctant Marvin agreed to collaborate with Abbot within the limits of the bureau’s resources, he clearly thought the entire idea of forecasting the weather on the basis of solar measurements in a South American desert was absurd.

By fall 1926 this controversy had grown hotter. Abbot claimed that it was possible to predict the weather a year in advance by his solar radiation method. Articles in the popular press implied that the “fundamentalists” running the Weather Bureau were just too conservative to embrace this revolutionary forecasting method. As John Billings Jr. wrote for *The Independent*, “[Abbot’s] pioneering with solar radiation forecasts has set the tom-toms of the conservative meteorologists beating wildly. The official Weather Bureau, plodding along carefully with day-to-day forecasts . . . would quickly crush [this theory] out of existence.” Marvin became so agitated while dealing with journalists over this controversy that his boss, Secretary of Agriculture William Marion Jardine, ordered him to stop talking to the press and “[observe] the dignified silence compatible with [your] official position.”³⁵ Despite Abbot’s arguments, Marvin refused to introduce solar radiation measurement as a forecasting technique until scientific evidence directly linked solar radiation changes and identifiable weather patterns. In the meantime, the idea that the Weather Bureau was a reactionary organization became more deeply entrenched in the American public’s psyche. Even though the bureau eventually showed that Abbot’s correlations had been due to seasonal variations in stratospheric ozone concentration, Abbot remained immune to the bureau’s criticism.³⁶

Abbot was not alone in promoting the influence of heavenly bodies on the weather. To the consternation of Weather Bureau leaders, some advocates of that notion were hired by the Department of Agriculture. In October 1934, Secretary of Agriculture Henry Wallace hired Larry Page, a statistician from Wallace’s home state of Iowa, to conduct studies of the moon and the stars. Page, who considered stars the “key” to the weather, was appointed to find how these extraterrestrial bodies could aid long-range weather forecasting.³⁷ Spending money that the Weather Bureau did not have on an idea that meteorologists considered cockamamie must have demoralized the entire forecasting section, not to mention the Weather Bureau’s new chief, Willis Ray Gregg, who took over from Marvin in 1934.

Despite arguments over using solar radiation measurements for forecasting, there was no disagreement over their use for agricultural purposes. The

bureau investigated the effect of shade cloth used by farmers, i.e., how much radiation needed by plants penetrated different cloth types, and the amount of heat generated by orchard heaters to prevent citrus and other orchard crops from freezing. The bureau conducted experiments on orchard heating (smudging) with the Army Chemical Warfare Service to determine if the smoke barrages, which the Army used to cover troop movements in the field, were effective against frost damage. The studies showed that the best way to protect vegetation from frost was to heat the surface layer by burning the cheapest fuel available.³⁸ These two investigations were directly related to preserving the economic value of agricultural commodities.

As noted above, the bureau was also responsible for monitoring volcanoes and earthquakes; seismological studies were mandated because they bore a “sufficiently close relation” to what the bureau did with the weather studies. Assigned to take on earthquake duties in 1914, the bureau’s mission with respect to earthquake studies and observations was to find and map fault lines and reduce damage to dams, bridges, and other structures by recommending locations away from potential slippage areas. Volcano studies included measuring lava flows and examining the compositions and reactions of volcanic gases. The bureau sought to determine any relation that might exist between volcanic activity and earthquakes, and between volcanic emissions and air and water. It also investigated if volcanic energy could be made available “for the use of man.” Relief came in 1924 when the US Geological Survey took responsibility for volcano studies.³⁹

Most, but not all, of the bureau’s climatological research was related to agriculture. One specific climatological study undertaken at the request of “other departments of the National government and for the use of the [1919] Peace Conference in Paris” dealt with Africa’s climate. In particular, the Weather Bureau was assigned to prepare a summary of African climate with special attention paid to former German colonies. The summaries included graphs of monthly precipitation and temperature values for the entire continent as well as a discussion of general climatic characteristics. What department made this intriguing request, or why, was not recorded, but the request illuminated the wide range of demands on bureau resources.⁴⁰

Of all its “research” tasks, however, the primary one was always forecasting—the improvement of short-term forecasts and the extension of the forecast period. The Weather Bureau routinely received requests “from all sides” for forecasts extending months, seasons, and years ahead.⁴¹ A Weather Bureau forecaster assigned to the station at Kansas City, Missouri, reported that he was once asked—in the winter—to name a date six weeks in advance when the “sun would shine and [the weather would] be otherwise pleasant” for

a bridge dedication. He did so based on climatological information and, by the kind of miracle occasionally bestowed upon weather forecasters, got it right.⁴² However, the forecast had “no skill”: it was no better than the state of climatology at that time. Skillful, accurate long-term forecasts would be of huge benefit to many business sectors. Farmers wanted advance knowledge of drought, excess precipitation, and extremely high or low temperatures. Road crews and transportation industries wanted to anticipate especially bad winters that could affect their ability to keep goods moving. Manufacturers wanted lead time to produce items needed by consumers. Retail outlets wanted to know what they should order.

However, the bureau’s leaders were steadfast in noting that there were, to their knowledge, no “sound physical laws” which would allow such forecasts to be made with any degree of success. This was made more complicated by those outside the science of meteorology and related fields such as atmospheric physics, sociology, and geology who claimed to have discovered methods of making accurate long-term forecasts. Even an economist fancied himself a long-range weather forecaster. The father of econometrics, Henry Ludwell Moore, published a long article in the *Quarterly Journal of Economics* that argued that the eight-year generating cycle in England, the eight-year crop cycles in England, France, and the United States, and the eight-year meteorological cycles could all be tied back to the motion of Venus with respect to the earth and the sun. The bureau was left in the position of sorting through public demands for long-range forecasts based on questionable methods that, upon closer inspection, did not yield valid forecasts. While not denying that it was possible to eventually make such forecasts, it did argue that forecast periods would not increase without solid scientific research.⁴³

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Well into the 1930s, the Weather Bureau doggedly defended its stance against long-range forecasts made without scientific underpinnings acceptable to the meteorology community—i.e., forecasting methodologies that did not include the physical processes of the atmosphere. Chief Charles Marvin’s 1930–31 report categorically stated that there was no “real way” to make long-range forecasts. The bureau was familiar with the literature on the subject. Available methods could be categorized as (1) examinations of physical processes that would lead to a specific weather condition, (2) periodicities or cyclical recurrences that correlated astronomical or other sequences of events with a specific weather event, or (3) mathematical

correlations between current weather in one location and weather that had occurred in the past, in the same or different location. None of these methods had resulted in any “skilled” techniques that extended the forecast period. A “skilled” forecast, by definition, had to be better than one derived from climatology data and persistence, i.e., the current day’s weather would persist into the next.⁴⁴

Bureau officials admitted that they had made very little progress in forecasting the weather in many years. By using radio to improve observational data transmission and airplane observations to gain knowledge of the atmosphere’s vertical structure, bureau personnel hoped to expand their understanding of atmospheric dynamics that would aid in attacking the forecasting problem.⁴⁵ But unbeknownst to bureau officials, a political storm was brewing on the horizon that would profoundly affect their operation.

The Weather Bureau’s leaders knew there were functional areas needing improvement, but viewed their work as being the best their budget allowed. The American Society of Civil Engineers, however, was not content with the services received by the engineering community. In April 1931, the ASCE’s Board of Directors appointed a special committee to “give thought as to how the United States Weather Bureau could be made of greater service to engineers.” The five-member committee presented its report at the ASCE Annual Meeting held 18 January 1933, and published the report in the January 1933 issue of the *Proceedings of the American Society of Civil Engineers*. A hot blast, their extremely detailed report laid out deficiencies the engineers had seen in the bureau’s operation of meteorological observation stations. It was followed by a series of letters, pro and con, which appeared in five subsequent *Proceedings* volumes.

The civil engineering report hit a raw nerve, and the ensuing uproar did not die quickly. Its engineers attacked observation station placement, data handling, and the format in which data were made available to engineers. They also impugned the scientific standing of the Weather Bureau, which, they charged, had “not kept pace . . . with research in other lines of science, either pure or applied.” After producing a list of recommendations, the committee members issued a final blast, recommending that upon the retirement of Charles Marvin the president of the United States should appoint a new chief from the ranks of those who were experienced administrators and who possessed “broad fundamental science training” and the “rare qualities of mature judgment and progressiveness.” Further, the new chief should be a “courageous [and] diplomatic leader, who will release the latent abilities now bound by archaic tradition.” There was one additional recommendation: the new chief need not be a meteorologist.⁴⁶

The ASCE was not the only group complaining. The Navy had been stung by the crash of the rigid airship USS *Akron* (ZRS-4) on 4 April 1933. The *Akron* had been operating off the coast of New England when high winds forced it into the water, where it sank. The accident killed 73 men, including the chief of the Bureau of Aeronautics, Rear Admiral William A. Moffett. A joint congressional committee investigated the crash, and the Navy held a court of inquiry to determine the disaster's causes. Since high winds had forced the *Akron* to crash-land in the water, all eyes turned to the data provided by the Weather Bureau. While Navy aerologists (the term used for weather officers) were required to provide aviators with detailed forecasts for periods longer than a day, the bureau's rather vague forecasts were for only 12 hours. More importantly, for several years the Navy Bureau of Aeronautics had been emphasizing the importance of taking four weather observations per day (instead of the Weather Bureau's two) to the Secretary of Agriculture, who had done nothing to increase the number of observations. After the *Akron* disaster, the Navy wanted action, and it was backed by the congressional investigating committee.⁴⁷ The Weather Bureau and the Secretary of Agriculture were under extreme pressure to quickly change their operations.

The loss of *Akron* and the ASCE report caused a firestorm that came to envelop not only the Weather Bureau but also Secretary of Agriculture Henry A. Wallace. Wallace (whose father, Henry Cantwell Wallace, had been Secretary of Agriculture in the early 1920s) was a graduate of Iowa State College. He had worked on the family's paper, *Wallace's Farmer*, becoming editor when his father took the Agriculture Department post. Wallace was also a plant geneticist who worked on corn hybridization. He was very interested in the connection between weather and crops, and he had close ties to the Weather Bureau. However, the ASCE report had become a political hot potato. The *Akron* disaster had the president's attention. Wallace had to address the complaints, or he would find himself under fire for supporting a purportedly non-scientific scientific bureau that could not provide the minimal weather support required for aviation safety. Looking for a way out of this potential quagmire, Wallace found a solution: the Science Advisory Board.⁴⁸

Established to study the functions, relationships, and programs of the government's scientific agencies, the Science Advisory Board had been created by President Franklin D. Roosevelt through Executive Order 6238 on 31 July 1933. The nine-member board, operating under the auspices of the National Research Council, came to be chaired by MIT's president, Karl T. Compton. Board members would offer recommendations to increase government agencies' efficiencies, and aid the nation in exploiting its scientific expertise. The board was concerned with this question: "How far should Government

itself go in conducting or supporting research or guiding the applications of scientific discoveries?"⁴⁹

Wallace contacted the head of the National Research Council, Isaiah Bowman, asking for help. Bowman recommended that Compton and Robert Millikan (then president of Caltech) serve on an advisory committee dedicated to addressing the Weather Bureau's problems. Bowman (a geographer by training) also suggested that Wallace consider the statistical records kept by the bureau and how they might come to bear on questions about the atmosphere. Wallace, then on the job less than 6 months, was frustrated with the lack of research funding available for the Weather Bureau. He felt "helpless" to answer the criticisms being heaped upon the bureau and, consequently, on the Department of Agriculture. In the darkest days of the Great Depression, and with the nation's farmers needing extensive assistance, Wallace did not have time to be encumbered by the Weather Bureau's flaws. He was therefore enthusiastic about Bowman's idea to bring in "outside meteorological interests" to improve weather services, to advance science, and to bolster the nation's defense.⁵⁰

In late August 1933, at Wallace's request, the Science Advisory Board created a Committee on the Weather Bureau. Because the members of this committee—Millikan (the chairman), Compton, and Bowman—were not meteorologists, Compton asked Charles D. Reed, a meteorologist in the Weather Bureau's office in Des Moines, to consult.⁵¹ Thus, the committee assigned to "assist" the Weather Bureau was unlike any of the others formed to study the government's scientific agencies: it was composed of scientists who were *not* experts in the agency's dominant discipline. Just as the astrophysicists felt entitled to claim that the sun alone determined the weather, two physicists and a geographer believed that they had a better grasp of meteorological practices than did the meteorologists.

The Committee on the Weather Bureau met with Charles Marvin on 26 August 1933. Bowman noted that Marvin—apparently oblivious to the fact that his days as chief were numbered—was "immensely pleased" with the committee's composition and with its mission. Marvin promised Millikan's committee his full cooperation.⁵²

The committee quickly homed in on the subject of meteorological research. Beno Gutenberg (a seismologist who had introduced meteorology courses at Caltech under the umbrella of geophysics) and Lieutenant Commander Francis Reichelderfer (the Navy's senior aerologist) had provided the committee written statements emphasizing the importance of introducing air mass analysis methods. This method, introduced by Vilhelm Bjerknes and his son Jacob at the Geophysical Institute in Bergen, Norway

(known in scientific circles as the “Bergen School”), had been available since the early 1920s. Reichelderfer had already introduced these techniques to Navy aerologists. While it did not appear that air mass analysis would significantly lengthen the forecast period, all of the committee members nevertheless believed it would lead to increased accuracy.⁵³

Wallace anticipated the committee’s first report on 1 November. Millikan volunteered to write the first draft. Committee members agreed that, to underscore their concerns about Weather Bureau’s structure and about expansion of research opportunities, they needed to make a case for economic benefits that would be favorably received by agriculture, commerce, and aviation. The report would include their recommendations on the adoption of air mass analysis techniques and the full range of Weather Bureau functions. However, committee members did not concur in the report of the American Society of Civil Engineers, which they found lacking (they thought the ASCE had failed to appreciate the Weather Bureau’s many responsibilities and the way it carried out its functions, particularly since the engineers’ primary complaint was that they needed to reformat the bureau’s data to make it useful for *their* purposes). The committee thereby eliminated one of Wallace’s concerns: he no longer had to worry about the engineers’ narrowly defined complaints.⁵⁴

The committee still had to address the matter of replacing the Weather Bureau’s chief. In early October, retired Weather Bureau meteorologist Oliver L. Fassig visited Isaiah Bowman. While Fassig ostensibly wanted to discuss tradewinds (he was working on a study of tradewind flow in Puerto Rico), his real mission was to discuss Charles Marvin’s replacement. Fassig argued that no one in the Weather Bureau had ever encouraged research. To his way of thinking, the bureau still suffered from “the old army spirit” from which it had sprung. The bureau needed someone from outside to come in. Fassig, however, could only think of one person he would recommend to be the new chief: Willis R. Gregg, a longtime Weather Bureau meteorologist. Perhaps more importantly, Fassig was worried that political influences could lead to a choice that ultimately would be detrimental to the bureau’s best interests.⁵⁵

By mid November, the committee had a preliminary report (which did not include a recommended replacement for Marvin) ready for Secretary Wallace. The report’s primary recommendation was that the Weather Bureau adopt the Bergen School’s methods of air mass analysis immediately, with Army and Navy assistance. The Weather Bureau needed the military services’ cooperation to expand the upper-air observation system (which had widely scattered stations; see figure 1.5) within its limited appropriated funds. The report also recommended that all data reporting and recording be assigned to the Weather Bureau. To fulfill these recommendations, the bureau needed

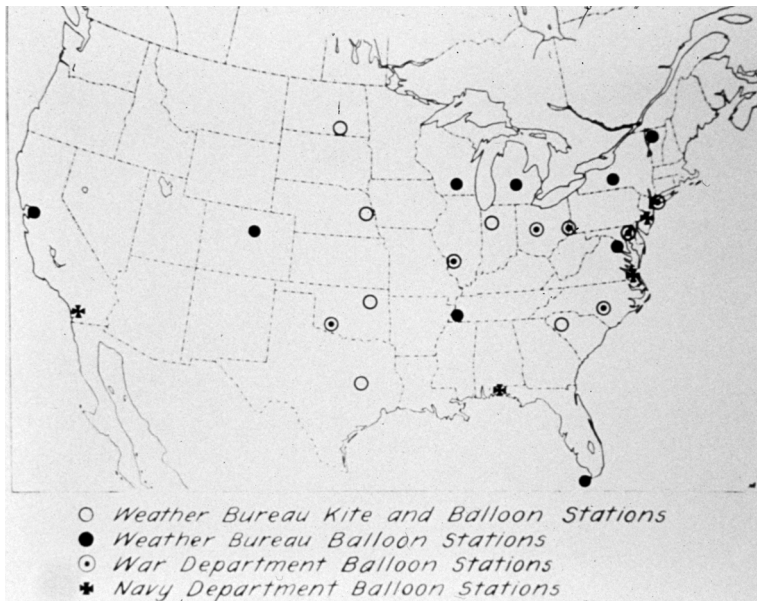


Figure 1.5

“Kite and balloon stations in the US,” circa 1925. (NOAA National Weather Service Collection, courtesy of NOAA Central Library)

to find and hire meteorologists who had training and experience in air mass analysis. It also needed nationwide daily reports of temperature and humidity up to 4 miles above the earth’s surface, as well as more frequent and detailed surface reports from both terrestrial and oceanic stations. However, improving weather services was not just a matter of more people and more observations. Even if the people and the reports were in place immediately (an impossibility due to Depression-driven across-the-board funding cuts), the bureau estimated that it would take 3–5 years to introduce the techniques to experienced forecasters. Army and Navy stations would provide additional upper-air data. Obtaining additional surface reports would be difficult: stations were manned to report only twice daily, but at least four daily reports, taken simultaneously around the country, would be needed to produce the four daily maps dictated by the Norwegian method. Congress had not appropriated additional money for expanded data collection, so the bureau could only hope to make limited progress with the new forecasting techniques. If it did not study and vigorously apply the results of new scientific work, the bureau realized, it would fall hopelessly behind other similar institutions. Indeed, it already had. European governments were

expending more money than the United States on research and applications, and the Bergen School's techniques were already successfully in use on the Continent.⁵⁶

While not heavily engaged in what would normally be called research, the Weather Bureau was responsible for publishing the only scientific journal in the United States devoted to meteorological research: *Monthly Weather Review*. In addition to publishing articles on scientific advances at home and abroad, *MWR* published recent and average weather records. The Weather Bureau also aimed to eradicate widely held "false ideas, which everywhere abound respecting the weather" and to assist those providing meteorological instruction in secondary schools and in higher education institutions.⁵⁷ Additionally, *MWR* fulfilled America's obligation to the wider international meteorological community by providing observational and statistical data related to meteorology and climatology. In return, the bureau received similar information from other nations. *MWR* published investigations of upper-air phenomena (including the strength and direction of air currents), articles on protecting agricultural products from weather extremes, and articles on the role of weather in health-related matters (termed "physiological meteorology"). *MWR* was the only journal publishing fairly long articles on meteorological research. Such studies vanished when *MWR* was crippled by Depression-era funding reductions. In 1932, *MWR*'s editor, the atmospheric physicist William J. Humphreys, stopped publishing articles as a cost-cutting measure—only the data portions remained in the journal. This action temporarily eliminated the one medium for exchanging new meteorological information worldwide, further hindering disciplinary advancement. Funds were restored almost a year later, at which point Humphreys requested immediate submission of completed articles.⁵⁸

Monthly Weather Review was only one of many research-related line items that were cut. In 1932, the entire government research budget was reduced by 12.5 percent. That included the Weather Bureau's scientific work not falling directly under the heading of research.⁵⁹ This loss of funding directly affected the bureau's ability to pursue climatological work.

Even more problematic than its paltry research budget was the Weather Bureau's inability to hire and keep scientifically trained staff members. Although the bureau's personnel situation most certainly deteriorated during the Depression, it had been plagued by personnel shortages for many years. Indeed, the War Department and the Navy Department had had few personnel trained in meteorology before the United States entered World War I. Since the majority of people with meteorological training (professional and technical) worked for the Weather Bureau, it had been responsible for providing both personnel and training to the war effort. Despite the resulting

increase in demand for services, starting in 1914 the bureau had experienced a *decline* in personnel, even as foreign meteorological bureaus were growing. Funding had not kept up with expenses or the expansion of services. Congress had turned down a request for additional fiscal year 1921 appropriations to cover aerological work in support of military and civil aeronautics, data gathering, and forecasting in support of marine meteorology (the bureau was responsible for open-ocean forecasting), and data gathering and forecasting related to fire-weather, fruit-frost, and other specialized agricultural-related missions. As the Weather Bureau's chief declared in his 1919–20 annual report, stagnant appropriations coupled with rapidly rising costs for goods and services had crippled his ability to meet new obligations. The number of weather stations was not adequate to support aviation, even with the addition of Army and Navy stations. Limited personnel had forced cutbacks in services, and demands by the insurance industry for timely, accurate data were taking a heavy toll. Chief Charles Marvin had explained this as follows: "In general terms, the Weather Bureau is suffering from the ravages of the war and the consequences of an enormous change in economic conditions. Its work is conducted under strained conditions by faithful personnel, largely discouraged by the slow and inadequate adjustment of Federal compensations to existing conditions of life." During the 1920s, increasing numbers of employees were leaving the bureau—some after 30 years—because their salaries did not support their families. Annually, 100 percent of the lower civil service grades turned over: the bureau was training meteorological observers who then left for better-paying jobs. Meteorologists with a bachelor's degree working for the Army Signal Service started at more than \$2,500 per year, while Weather Bureau meteorologists (with master's degrees and 10 years of experience) only earned \$1,800 per year—less than most shop employees earned at the Bureau of Standards or than most clerks received at the Department of Agriculture's Office of Experiment Stations. Nor was the salary discrepancy between the Weather Bureau and other science-based agencies limited to the lowest levels. In 1921, the Weather Bureau's chief was paid \$5,000 to lead an organization with more than 200 stations and a budget of \$2 million. While the chief of the Office of Experiment Stations received the same salary, he supervised an organization with only five stations and a budget of \$250,000. The chief of the Bureau of Chemistry and Soils was paid \$8,000. His organization's budget was only \$1.3 million.⁶⁰ The Weather Bureau was unique in this discrepancy between wages paid and corresponding levels of responsibility. No wonder the Weather Bureau, as an organization, carried itself in the manner of one who has been constantly put upon. Weather Bureau employees *were* put upon. They were given neither the

respect nor the corresponding remuneration accorded to employees of other scientific agencies.

In 1924, the Civil Service reclassified positions to align the pay scales for similar positions across government agencies, but Weather Bureau employees were still paid inadequately (considering level of education and training, responsibilities, and length of service) relative to other civil servants.

By the early 1930s, the Weather Bureau was seeking additional employees to provide aviation services. However, it had a difficult time finding enough trained men (there were no women in the bureau). Senior grades required degrees in mathematics or physics, preferably with some meteorology courses. However, so few colleges offered separate meteorology courses that the bureau could not make them a requirement for employment. All positions, regardless of educational background, were filled by competitive civil service examination.⁶¹

The personnel situation had deteriorated further once the government instituted Depression-era economy measures. In mid 1932, men over the age of 70 (with a few exceptions) were immediately retired. With this cut the Weather Bureau lost 25 of its most senior people, including two-thirds of those with earned PhDs. Of the latter, only three (Chief Charles Marvin, a meteorological physicist, and the head of the New Orleans field office) kept their jobs. Most of those retired had been heading field stations—a position for which the most important indicator of probable success was years of experience. Those remaining within the system lacked equivalent education and training. This situation adversely affected the bureau's ability to provide effective weather services.⁶²

In 1933, the Weather Bureau endured more funding reductions and personnel losses. Congress appropriated \$400,000 less for fiscal year 1934 than for 1933. It then imposed a spending limit that was an additional \$800,000 below the appropriation—a total loss of \$1.2 million. The final budget was just shy of \$3 million. As a result, the bureau laid off 500 employees and closed more than twenty first-order stations (including those at Fort Worth, St. Paul, and San Jose) and a large number of substations. A number of departments (particularly Agriculture and Commerce) lost weather services due to the budget cuts. Worse yet, the bureau lost additional senior personnel. Many of those with 30 or more years of service were involuntarily retired. Some of the remaining employees kept their jobs by moving into lower-ranking positions. Along with everyone else in government, they took a 15 percent pay cut—not an incentive for recruiting younger meteorologists.⁶³

Weather Bureau employees thus had many concerns during this period: loss of jobs, pay, and funding for goods and services, and intense pressure to maintain consistent, high-quality weather services. Therefore, it had been

especially irksome to receive complaints from entities such as the American Society of Civil Engineers that Weather Bureau data were difficult to use. An ASCE committee looking into the bureau's methods found personnel to have an "inferiority complex," enhanced by weaker educational backgrounds and inadequate equipment for scientific investigations, compared to those working elsewhere in the Department of Agriculture. Oliver Fassig (the former chief of the climatology division, who had been involuntarily retired) fired back that the Weather Bureau did not exist to support special-interest groups. Furthermore, the bureau was still hampered by the attitude toward meteorology as a science that existed during its establishment in the late 1800s, i.e., it was not a "real science" like physics or chemistry. As a result, it suffered from long-standing "poor intellectual visibility."⁶⁴

In 1935, the bureau began to climb out of this desperate situation when it hired three young meteorologists with newly earned MIT PhDs: Horace Byers, Harry Wexler, and Stephen Lichtblau. Their mission was to bring the Norwegian polar front and air mass theory—a theory recommended by the Science Advisory Board—to the bureau. Their mandate was to study how Bergen School techniques could be applied to North American weather, and then teach them to field meteorologists. But the addition of these three young men did not markedly improve the bureau's educational profile. Surveying personnel in the late 1930s, Byers found that only 27 percent of "professional personnel" had college degrees, and that half of those degrees were in science or engineering. By 1939, there were only five Weather Bureau employees with meteorology degrees.⁶⁵ This dearth of professionally educated meteorologists was largely due to the low opinion held by academe about meteorology as a scientific discipline before World War II.

Stagnant and then dwindling appropriations kept the Weather Bureau in a rut. Reduced funding exacerbated already low salary levels and the bureau's inability to expand observation stations. With no research budget, the bureau was not able to analyze the data it had collected from its 5,000 volunteer observers. With little congressional support, it had not sought out new analysis and forecasting methods until prodded by the Science Advisory Board. As the 1930s closed, long-range forecasting and mathematics-based objective forecasting techniques appeared to be in the distant future.

Looking Abroad for Inspiration: The Navy Aerological Service

Like the Weather Bureau, the Navy Aerological Service (Navy Aerology for short) had long operated with limited funds and manpower and with

virtually no support from the battleship admirals leading the Navy. But unlike the Weather Bureau, the Navy had looked to the Bergen School and adopted its methods—a decision that would inform, shape, and strengthen the professional relationships between several major figures who would eventually influence the development of numerical weather prediction in the United States.

Having transferred its marine meteorological service (minus the weather information plotted on pilot charts) to the Weather Bureau in 1904, the Navy had paid scant attention to meteorological services until World War I. Then, demands from aviation units forced it to expand its meteorological mission. After the war, as discussed above, the bureau had resumed its role as the nation's sole provider of weather services. However, it soon became obvious that the bureau was not going to have an office near every one of the naval activities that were scattered along the Atlantic, Gulf, and Pacific coasts. "It is fully recognized," Secretary of Agriculture David Franklin Houston wrote to Secretary of the Navy Josephus Daniels on 14 January 1920, "that certain meteorological work and observations must of necessity be conducted by the Navy in connection with its operations at base stations and on vessels at sea, but such work does not involve duplication of effort. In fact, stations so maintained by the Navy will supplement those of the Weather Bureau and be valuable to it."⁶⁶

The Navy's aerological mission would be to provide "detailed weather information to naval aviators and aeronauts" and to provide local weather forecasts when a Weather Bureau office was not close by.⁶⁷ That did not seem too onerous a task; however, with only five officers and two enlisted men remaining from war service, the Navy was far from able to meet all requests for meteorological support.

Because almost all weather observing and forecasting tasks had been absorbed by the Weather Bureau in the earliest days of the twentieth century, the Navy was not prepared to fill a rapidly expanding need for meteorological support. It had no meteorological specialists and only a few basic instruments. Naval air stations were very interested in obtaining "allowances" for meteorological equipment and personnel. While an "allowance" would not guarantee equipment and personnel, without an allowance naval air stations would never get them. However, sailors were unfamiliar with meteorology, and civilian meteorologists were unfamiliar with the Navy, so it took some time to put a new Navy meteorological organization together. Starting in 1917, Alexander G. McAdie, director of the Harvard-affiliated Blue Hill Meteorological Observatory, began to provide meteorological training to officers in conjunction with MIT's aviation ground school. At the request

of Assistant Secretary of the Navy Franklin D. Roosevelt, McAdie accepted a reserve commission as a lieutenant commander in January 1918 and began to determine the Navy's aerological needs and organize an aerological service. Shortly thereafter, enlisted personnel started receiving meteorological training at Pelham Bay, New York. The Navy shipped 9 officers and 15 enlisted men to England for further training with the British Meteorological Office and then on to European assignments for the war's duration. By war's end, 50 officers and 200 enlisted men were providing meteorological services to a variety of naval activities.⁶⁸

When the Navy determined that it had to accept responsibility for most of its own weather support, it was obvious that the seven remaining meteorological personnel could not fulfill the mission. Naval activities at home and abroad, as well as afloat units, needed weather forecasts. Because weather conditions were important to flight safety, the Navy established a meteorology school at Naval Air Station Pensacola, home of the flight school. Training for both officers and enlisted men covered the science of meteorology and its applications to naval operations. Enlisted men took a four-month course that prepared them for assignments at naval air stations, on aircraft tenders (ships that provided repairs and maintenance to seaplanes), and with other ships and stations. In addition to this in-house instruction, Weather Bureau headquarters provided some naval officers with two additional months of "post-graduate study." Of the six officers who graduated from the basic course, three went directly to field assignments, while the other three moved to Washington for further training. This advanced course included non-instrumental observations of weather (e.g., the significance of particular cloud types), discussions of flying weather, weather map construction, discussion and forecasts, and physics of the air. The bureau also gave the visiting officers free access to its library.⁶⁹

Despite the Navy's laudable effort to establish a training program that would boost its numbers of meteorologically trained personnel, any naval officer who planned to maintain a successful naval career had to spend a considerable amount of time at sea or serving with the nascent aviation units. Consequently, receiving meteorological training was not high on the list of desirable career options. With insufficient volunteers, the Navy ordered officers who had little or no interest in meteorology to the training courses. They stayed within the aerological program for the minimum required time before transferring to more career-enhancing positions. These uninterested officers tended to lead inefficient weather stations, which contributed to weather-related aircraft incidents. In the worst of these accidents, the rigid airship *Shenandoah* went down in a line squall on 3 September 1925, killing

14 people. Coming just one day after the disappearance of two Pacific-based PN-9 seaplanes in the Pacific, the case for the necessity of good weather support had been made.⁷⁰

The Navy needed to take a different approach to maintain a cadre of highly trained meteorologists who could apply their knowledge to naval operations. The difficulty: line officers, i.e., “warfighters” serving afloat, already considered themselves to be good weather forecasters. They spent their lives at sea and had to be able to read the skies for indications of future weather conditions. They felt no need for advanced training. Furthermore, remaining in a specialty area like aerology would have effectively ended their careers. Promotions depended on filling shipboard “combat” positions. Making weather forecasts to aid the fleet was not sufficient to guarantee advancement. Despite the training program in Pensacola, by 1925 there were only two naval officers practicing meteorology. One of them—Reichelderfer—was eventually destined to become the Chief of the Weather Bureau.⁷¹

Francis Wilton Reichelderfer had graduated from Northwestern University with a degree in chemistry in 1917, just as the United States was entering the Great War. Joining the naval reserve intending to become a pilot, he signed up for meteorology training and was assigned to Alexander McAdie’s training unit at Blue Hill. Reichelderfer did earn his wings after the war was over, but he remained in the meteorological field. By 1922, he was the head of Navy Aerology (a position he held until 1928) and occupied the Navy’s “desk” at the Weather Bureau’s headquarters, where he filled a liaison function while pursuing his own studies of Bergen School techniques. With the demand for aviation forecasting increasing as the numbers of meteorological practitioners dwindled, Reichelderfer decided that the only solution was to establish a post-graduate course for Navy meteorologists. In 1926, Reichelderfer (by then a lieutenant commander) and Edward P. Warner (an MIT professor of aeronautical engineering who was serving as Assistant Secretary of the Navy for Aeronautics) established a two-year post-graduate course in meteorology. Reichelderfer argued that the importance of weather information for aviation missions was new and distinct from the previous use of forecasting to ensure safety at sea. The Weather Bureau took care of marine forecasts. The aviators needed special weather information (e.g., on cloud layers, fog, and strong winds) to make decisions on launching aviation missions that could include scouting and bombing. Because that kind of detailed information could not be transmitted via teletype, an officer needed to be on site to provide “over-the-counter” briefings and to answer questions.⁷²

The Navy taught the first year of this new course, emphasizing advanced physics and mathematics, at the Naval Postgraduate School on the US Naval

Academy's campus in Annapolis. The second year, concentrating on meteorology, had to be taught elsewhere. Reichelderfer approached climatologist and eugenics proponent Robert DeCourcy Ward of Harvard about the possibility of hosting the course. Ward agreed to host it for one year, if MIT's physics and mathematics faculty would teach dynamic meteorology (which deals with the solution of hydrodynamical and thermodynamical equations as related to the full range of atmospheric motion). At the end of the first year, neither MIT nor Harvard had the faculty to carry out the Navy's proposed instructional program. However, MIT's Warner had convinced the Daniel Guggenheim Fund for the Promotion of Aeronautics that support for aeronautics meant more than research on aircraft design and construction. Meteorological instruction and research leading to more accurate forecasts were essential for safe flight. The Guggenheim Fund gave MIT \$34,000 to fund the first 3 years of a meteorology course, and provided Carl-Gustav Rossby to lead it.⁷³

The Swedish-born Rossby would in time emerge as the most influential theoretical meteorologist of the middle years of the twentieth century. He had studied mathematics, mechanics, and astronomy at the University of Stockholm before moving on to work with Vilhelm Bjerknes at the Geophysical Institute in Bergen. After two years there, he studied hydrodynamics at the University of Leipzig's Geophysical Institute. Returning to Sweden in 1921, he took a position with the Swedish Meteorological and Hydrological Institute while he completed his *filosofie licenciat* in mathematical physics at the University of Stockholm. Awarded a fellowship by the American-Scandinavian Foundation to study in the United States, the energetic, hard-driving Rossby joined the Weather Bureau's headquarters staff. While working on questions related to atmospheric turbulence, he attempted to persuade bureau forecasters to use Bergen School techniques. Weather Bureau meteorologists were not receptive, but Francis Reichelderfer was. A friendship blossomed, and this pair of meteorologists would continue to work together to advance the discipline until Rossby's death in 1957. Rossby, having irritated the Weather Bureau hierarchy and needing another position, was invited by the Guggenheim Fund to organize weather services for its model airway being constructed between Los Angeles and San Francisco in 1928. Once the weather services were turned over to the bureau, Rossby was available to lead the new MIT meteorology program.⁷⁴

Rossby established the course at MIT (within the department of aeronautical engineering) with the help of synoptic meteorologist Hurd C. Willett. (Synoptic meteorology is the subdiscipline that coordinates observations into a picture of the day's weather and makes predictions of future weather.) Willett had joined the Weather Bureau after graduating from Princeton in

1924, and subsequently spent time studying with the Bergen School. He was completing his PhD at George Washington University when he joined the new MIT program. The new curriculum included course work in physics of the air, and mathematical and dynamical meteorology, and practical work in forecasting. Reichelderfer hoped that the course would “arouse more general interest throughout the country in instruction in weather science and [lead] to fruitful research and development.”⁷⁵

MIT’s new graduate program, based on Bergen School techniques, provided the Navy with a cadre of formally trained meteorologists. By 1934, 24 officers had attended and were working as aerologists. However, there was a continued lack of upward career mobility, and in 1940 only 18 would remain.⁷⁶ Thus, once again, the Navy would enter a war without sufficient personnel to provide the required meteorological support to the operating forces.

With so few meteorologists and with no research budget, the Navy aerologists, like their Weather Bureau counterparts, had little opportunity to implement new ideas and techniques. Despite these difficulties, Reichelderfer had circulated Jacob Bjerknes’s first paper on frontal analysis techniques to his fellow Navy officers by 1921 and started applying those techniques to surface weather maps shortly thereafter. He actively sought papers written by Bergen School members and distributed them to colleagues. Therefore, Navy officers attending graduate school were familiar with the Norwegian methods. The Norwegian methods were also taught to Navy aerographer’s mates (enlisted men) at the Aerology Observatory in Lakehurst, New Jersey, site of the airship base. While Reichelderfer was in Lakehurst to forecast for airship operations, he had Rossby’s MIT group mail their daily weather maps to him. Even though the aerographer’s mates were being trained in Bergen School methods, Reichelderfer noticed that their maps did not match the MIT maps. It was obvious to Reichelderfer that to successfully train the aerographer’s mates in Bergen School techniques he needed to go to Norway.

En route to Norway in 1931, Reichelderfer spent almost a month with the British Meteorological Office to examine their organization and forecasting methods. A six-month stay in Bergen followed. Reichelderfer also visited weather offices all over Europe (including France and Germany), writing enthusiastically detailed accounts of their operations. He sent these reports (marked “Restricted”) via diplomatic pouch from the US Embassy in Paris under naval intelligence cover sheets. Upon Reichelderfer’s return, one of his new Norwegian colleagues traveled to the United States to lecture Navy aerologists. This led to what Reichelderfer later termed “successive invitations by universities that led to permanent residences by some of the well-known and distinguished Viking scientists.”⁷⁷ Thus, the efforts of both Rossby and

Reichelderfer to promote Bergen School methods significantly influenced the eventual immigration of Scandinavian meteorologists to the United States. This influx of Scandinavian expertise would have a tremendous impact on the advancement of meteorology in America.

Mid-1930s newspaper articles typically described this “new” air mass analysis method to be of recent American origin, though in fact it was a Norwegian import. Infrequent weather observations, coupled with inadequate spatial distribution, impeded its full implementation.⁷⁸ To be effective, weather observations had to be taken nationwide every six hours, and data density had to increase. This was not a small concern for the Navy, which obtained all weather data from the Weather Bureau, whose budget could barely handle current requirements.

The Navy was also actively encouraging (and carrying out) the collection of upper-air observations. In the mid 1930s, Navy aerologists became the first to use special recording instruments (meteorographs) attached to airplanes to obtain temperature, pressure, and humidity data, which could then be used for local area forecasting and to supplement Norwegian methods. Navy Aerology was committed to staying current with the latest scientific developments—coming primarily from overseas—so as to advance meteorology in the United States and stand ready to fulfill its duties in war and peace. Weather forecasts for flight operations, visibility forecasts for the accurate firing of shipboard guns, and wind forecasts for ballistic targeting would all be important as the Navy prepared to enter another war in the late 1930s.⁷⁹

Fighting to “Ground” Meteorology: The Army Signal Corps

The Army Signal Corps (Meteorological Division) had a longer history than either the Weather Bureau or the Navy’s aerological service. Weather services in the United States had been a function of the Army Signal Corps from 1870 until their transfer to the Department of Agriculture in 1891.⁸⁰ The War Department then depended on the Weather Bureau for meteorological support until World War I.

Unlike earlier armed conflicts, the Army had recognized that weather support would be crucial to its success on the battlefield as it prepared to enter the war. Weather services had not become important because predictions were significantly better, or because Army leaders had determined that weather conditions affected battles. Rather, weather prediction mattered because advances in armaments dictated requirements for meteorological support. Artillery ranges had increased to ten miles or more; atmospheric

conditions, winds in particular, influenced targeting. Army units were also using listening posts to determine the location of enemy artillery batteries. Known as “sound ranging,” the accuracy of this woefully inadequate method decreased dramatically without knowledge of air density, and wind speed and direction. The successful use of poison gas depended on favorable winds. High winds blew the gas over enemy trenches or dispersed it too rapidly to be effective. Light winds carried the gas so slowly that the enemy could take countermeasures. If the wind shifted, it would drift back over friendly forces—an event that, as one contemporary observer noted, “seriously interfere[d] with the career of the gas officer.” Therefore, accurate knowledge of the wind regime was very important. And, of course, the introduction of aviation assets meant flight forecasts. The Air Service of the American Expeditionary Force was one of the first Army organizations to require weather support. These early aviation forecasts had been for safety, not tactics. Their purpose was to keep these planes built from “wood, glue, wire, and fabric” out of adverse weather—high winds, turbulence, and hailstorms—that could bring them down.⁸¹

General John Joseph “Black Jack” Pershing, Commander of the American Expeditionary Force, had requested meteorological personnel. Like the Navy, the Army did not have enough meteorological officers to meet the demand. Not only did Pershing need meteorologists in wartime Europe; the Weather Bureau could not support the Army’s stateside activities—the Gas Warfare Service, ordnance proving grounds, and field and coast artillery units.⁸²

Manpower, not surprisingly, was hard to find. The Chief Signal Officer, General G. O. Squier, had called on the National Research Council to recommend possible sources of potential officers. Squier also had asked the Weather Bureau for help because “virtually all the trained meteorologists in the country were employed by the [bureau].” A planning committee composed of bureau personnel was led by Lieutenant Colonel Robert Millikan, then serving as the Officer in Charge of the Signal Corps Science Research Division. The committee determined that available assets had to be divided among three basic support areas: the American Expeditionary Force, the stateside activities needing weather services, and research into meteorological topics. To solve the manpower shortfall, the bureau had donated 25 percent of its 600 employees to the Army through the end of World War I. Hundreds more were trained—some at Texas A&M (figure 1.6)—just for wartime military service.⁸³

The Signal Corps’ provision of weather services was one part science, one part military tactics. Meteorology personnel faced challenges that fell into one of three categories. First, they had to develop statistical meteorology (i.e., clima-

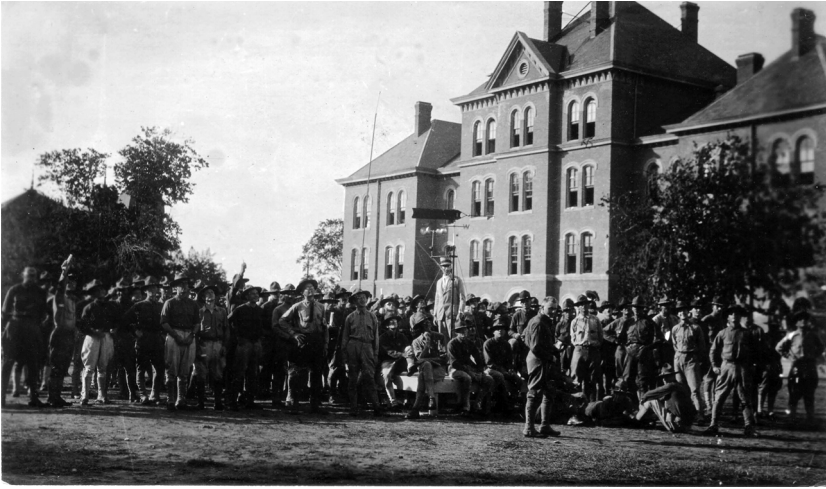


Figure 1.6

Army Signal Corps meteorology training during World War I. These young trainees at Texas A&M are watching the launch of a weather balloon. (courtesy of Military Heritage Institute, Carlisle Barracks, Pennsylvania)

tology) to determine appropriate locations for military units and aerodromes. Second, they had to provide current meteorological information to military units, including ballistic winds to artillery companies, humidity, temperature, and wind data for sound ranging, and pilot-balloon and theodolite observations for aviation. Third, they had to provide forecasts in advance of military operations. Observers had to measure temperature, air density, and wind direction and speed so artillery units could exploit sound ranging and properly aim their guns.⁸⁴

Cobbled together just as the United States entered the war, the meteorological division performed well during the conflict. Unfortunately, like their Navy brethren, meteorological personnel had left the Army in droves and returned to their peacetime occupations after the war. However, the mission remained. Planes were still flying. The Chemical Warfare Service had continued to conduct experiments and practice maneuvers. The field artillery units still needed standard ballistic range tables for their artillery pieces.⁸⁵

Despite the hundreds of men trained in meteorology in World War I, between 1921 and 1935 no more than eleven weather officers served in the Signal Corps. Along with a handful of enlisted men, they were able to fulfill less than one-fifth of the demand for their services. The Signal Corps continued to build more weather stations (they quadrupled the number to approximately 40), but with so few soldiers the quality of meteorological services remained poor.

The Signal Corps trained both officers and enlisted weather personnel at Camp Vail (later Fort Monmouth), New Jersey, which also was home to meteorological instrument development. Additional enlisted men received meteorology training at Carlstrom Field (Florida) and March Field (California) as part of flight training. With close ties to the Weather Bureau, which was providing most of the forecasts, the Signal Corps took no interest in the Bergen School techniques. When Reichelderfer offered Signal Corps leaders the chance to participate in the Navy's new MIT graduate program, they declined.⁸⁶

The Air Service had not been content waiting for the Signal Corps to upgrade weather support. From 1922 to 1924, the meteorology section's budget more than doubled from \$27,000 to \$67,000—and it was all due to Air Service requirements. As far as the Air Service was concerned, meteorological services belonged under its jurisdiction. The Signal Corps argued that weather services were not exclusive to the Air Corps. Therefore, the meteorology section stayed within the Signal Corps, but fell under the Intelligence Division, having escaped from the Special Services Division that supervised the Pigeon, Photo, and Commercial sections.⁸⁷

From the mid 1920s on, a power struggle ensued between the older Army "ground pounders" and the younger aviators. The latter wanted more support. The former had control and intended to retain it. The Signal Corps did not care much about the Meteorology Section, and probably could have been forced to give it up. However, the Air Service was fighting for survival within the military structure and did not have the time or the energy to become embroiled over what seemed like a minor point.⁸⁸ Although the Air Service was not effectively fighting for control over meteorology, it did accept Reichelderfer's offer and sent its first student to MIT in fall 1929. However, Air Service meteorologists did not embrace Bergen School methods until 1935.⁸⁹

In 1934, the Signal Corps' chief declared that he wanted release from the weather mission if he did not get more funding. But that same year, charges that the US Post Office had fraudulently awarded air mail routes without competitive bidding (later shown to be unwarranted) led Post Office Solicitor Karl Crowley to declare that existing contracts were void. President Roosevelt then issued Executive Order 6591, which canceled all air mail contracts and ordered the Army to carry the mail. The Army Air Service took over the flights with only ten days' notice. This was an ill-fated decision. Not only were Army aircraft inferior to anything being flown by commercial carriers, the weather was particularly bad and the forecasts were inadequate. Within three weeks, twelve pilots died in airplane crashes. Although this decision became a political liability for Roosevelt, the Signal Corps bore the brunt of criticism for its forecasting deficiencies. The Signal Corps' gambit to use this fiasco to obtain

additional funds did not work, however, and the Air Corps, which had more weather-trained officers than the Signal Corps, took over weather forecasting responsibilities as the primary user of the services.⁹⁰ Commenting on the divorce of meteorology from the Signal Corps, one officer later testified that meteorology had “no more to do with signals than Donald Duck.”⁹¹

In 1937, the Air Corps began sponsoring weather services for aviation and for ground forces serving in units at the division level or above. Signal Corps weather officers desiring transfers had to qualify as pilots—a requirement that did not encourage movement of trained personnel. Enough personnel were attracted to this new meteorological service that by the end of 1939 30 officers and almost 400 enlisted men were serving in the Air Corps.⁹² Even this increase would not be nearly enough to provide for the requirements of the by then rapidly approaching war.

While the forecasting mission moved to the Air Corps, the limited meteorological research function remained within the Signal Corps. Most research and development activities were centered on meteorological instruments. Despite pressure to move this work to Wright Field in Ohio due to aviation requirements, it remained at Camp Vail. The Army needed meteorological support for all of its forces, not just the aviators.

The work at Fort Monmouth later proved critical for the eventual development of numerical weather prediction models. The researchers worked to develop an audiomodulated radiosonde (then called a radiometeorograph). This instrument would allow upper-air observers to gather data during the night or during cloudy weather—whenever a pilot balloon would normally be obscured. Large balloons carrying meteorological instruments and a radio transmitter would send data to a receiving station, which was far superior than trying to find the recording equipment after it had fallen back to the ground. The Army also conducted meteorological research related to chemical warfare. The Chemical Warfare Service sponsored almost 700 projects for the Army, the Navy, and civilian organizations. However, appropriations were so small (less than \$1 million annually for all projects combined from 1923 to 1926, and less than \$2 million annually from 1927 to 1938) that each project received an average of 2–3 thousand dollars. Most research was directed, not to basic weather research or prediction, but toward the effects of micrometeorological phenomena on the movement of gas.⁹³

In Retrospect: Weather Services in the Interwar Period

While European weather services were relatively awash with money in the period between the two world wars, encouraged research, and eagerly tried

out the new ideas of the Bergen School, the United States experienced a period of retrenchment for all of the weather services. For example, while the Norwegians and the Germans funded geophysical institutes to conduct meteorological research, the Americans did not. The military services experienced dramatic drops in personnel and funding immediately after World War I, from which they did not start to recover until war loomed once again. The Weather Bureau, forced to operate without almost a quarter of its personnel during World War I, got them back, only to face stagnant appropriations in the 1920s, then drastically reduced appropriations as the Great Depression deepened.

Losing its most experienced personnel, and having no opportunity to replace them, the Weather Bureau could barely provide routine services, much less expanded aviation services. With low levels of funding and compensation, and with a training program that assumed that the only way to create a forecaster was through an apprenticeship of 5–6 years, it is hardly surprising that the bureau was not in the forefront of implementing new forecasting techniques. Furthermore, astrophysicists, statisticians, economists, physicists remote from atmospheric work, and others were telling the Weather Bureau how it should be doing its job. What could have been more demoralizing for government meteorologists than repeatedly being told, through words and deeds, that their scientific discipline did not deserve to be included with the scientific “big boys”?

The Navy Aerological Service had suffered more from benign neglect. Sea captains, believing they knew everything there was to know about the weather, were perfectly satisfied with their ability to operate under any conditions. For decades, they (and commanders of entire fleets) failed to consider the influence of weather on naval operations. However, operating in weather extremes was just part of fulfilling the Navy’s mission at sea. This confident devil-may-care way of thinking did not last as long in the aviation community. The atmosphere is much less forgiving to aircraft under less than perfect conditions. Therefore, aviators demanded increased meteorological support even while the Navy did not provide a career path for those who would provide it.

The interwar period saw the Navy adopt and spread Bergen School methods through its own professional networks in a way that did not occur in the much larger Weather Bureau, still top-heavy with older men. Thus, when the Science Advisory Board directed the adoption of air mass analysis techniques, the Navy was able to meet the requirements with less resistance. Instruments were being developed and put on aircraft to gather data, which were then shared with the Weather Bureau. In this way, the Navy was looking forward. What it could not see was how once again it was approaching a time of war with insufficient personnel to fulfill its mission.

As World War II loomed, the Meteorology Section of the Army Signal Corps was probably in the worst shape of all the weather services. It was a low-priority organization, thrown together with the messenger pigeons. Aviation units received their forecasts from the Weather Bureau. With no war in sight for the United States through the 1920s and into the 1930s, there was little concern about providing meteorological services to ground troops overseas. Research was almost exclusively focused on developing and improving meteorological instruments. Although these newly developed instruments, in particular the prototype radiosonde, greatly enhanced meteorologists' ability to collect upper-air data, the success of that endeavor was not sufficient to keep the Signal Corps' Meteorological Section going. Scant attention was paid to new developments in the atmospheric sciences and the old methods—good enough for the Weather Bureau—were good enough for the Signal Service. It was not until the end of this period that the Air Corps prevailed and the meteorological mission was moved out of the Signal Corps. The focus then shifted to keeping aviation assets (pilots and aircraft) safe and effective.

Meteorological services advanced in very limited ways in the United States between the wars. Instrumentation improved primarily through the efforts of the Signal Corps' research arm and because of the interest of instrument specialist Charles Marvin, then Chief of the Weather Bureau. High profile criticism of the Weather Bureau had prompted Secretary of Agriculture Wallace to make the politically expedient move to call in outside "experts" in the guise of the Science Advisory Board to recommend ways to "fix" the bureau. However, many of the bureau's shortcomings are better attributed not to a failure of leadership, but to a failure of adequate funding for a government organization providing a free service that earned business and agriculture interests millions of dollars a year. Not even the distinguished members of the Science Advisory Board could secure the funding the bureau needed—it just recommended changes that the bureau could not afford.

And so America's weather services limped along, doing their best to ensure safety of flight, warn farmers and the general public of weather hazards, and get out a forecast that made sense. As the world marched steadily toward global conflict, the Weather Bureau, the Navy Aerological Service, and the Air Corps' new weather section would soon be put to a huge test—a test for which none of them was ready.

