Flying weather men and robot observers: instruments, inscriptions, and identities in US upper-air observation, 1920–1940

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From the early 1920s to the end of 1930s, US meteorologists implemented a program of weather observation flights by airplanes as a chief method of collecting data from the upper-air. The seemingly well-defined task of obtaining more weather data as quickly as possible posed serious technical and managerial challenges to the meteorologists, who struggled to fix both the transient air and the pilots’ risky weather flights. The relationship between meteorologists and pilots mediated through the recording instrument – meteorograph – reveals that the practices of collecting and representing scientific data were intimately entangled with various questions of professional identity, control in scientific practice, and the contested meaning of the ‘automatic.’ Putting the instrument and the project in this context enables us to understand why the new instrument ‘radiosonde’ that finally replaced the airplane method was called the ‘robot observer.’

Keywords: meteorologist; pilot; airplane; weather observation; meteorograph; radiosonde

Vilhelm Bjerknes, a Norwegian meteorologist now known as one of the founders of modern meteorology with his theories of air mass, explained the ‘relationship of mutual dependency’ between aeronautics and meteorology in 1909. On the one hand, the increasing use of airplanes would demand more accurate knowledge of the atmosphere to ensure safety. ‘On the other hand,’ Bjerknes continued, ‘meteorology, for its development is completely dependent on aeronautics in this word’s broadest meaning. It alone can provide the observations that will allow us to study completely the atmosphere’s laws.’ The advent of heavier-than-air flight excited the pioneer of modern meteorology. For Bjerknes and other meteorologists of his time, airplanes seemed to provide not only a strong justification for their burgeoning scientific discipline but also a revolutionary tool with which to study the upper atmosphere for both daily weather forecasting and scientific research.

One important aspect of this ‘relationship of mutual dependency’ can be found in the USA from the early 1920s to the end of the 1930s. During this period, American meteorologists implemented a program of weather observation flights by airplanes as a chief method of collecting data from the upper-air, until a new instrument called ‘radiosonde’ finally replaced the airplane method. The introduction of the radiosonde – a balloon-borne instrument that records weather data such as air temperature, pressure, and humidity and transmits them by radio to a ground receiver – in the 1930s is often listed as one of the major breakthroughs in modern meteorology, along with the development of the air mass theory by Bjerknes and his group. The authors of a comprehensive historical study of the radiosonde assert that its ‘contributions … to the late twentieth century way of life can hardly be exaggerated.’ Not only was it crucial to ‘the systematization of weather observations,’ the

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radiosonde technology also ‘directly affected agriculture and aeronautics’ and served as a platform for ‘many of the marvels of the space age.’\(^3\) By contrast, the method of airplane sounding has received much less historical attention.\(^4\) This seems to reflect the overall judgment by meteorologists and other scholars that the radiosonde method was simply superior in technical performance and played a more prominent role in the development of meteorology and weather forecasting. This essay is not an attempt to assess the relative scientific significance of the two observation methods. Instead, it will examine the historical actors’ assumptions and practices in weather observation as expressed through the interplay of various flight technologies (aircraft, balloons, and kites), pilots, meteorologists, institutions, scientific instrumentation, and data collection.

More specifically, a closer look at two methods of weather observation – balloons and aircraft – reveals how the practice of collecting and representing scientific data was intimately entangled with various questions of professional identity, control in scientific practice, and the contested meaning of the ‘automatic.’ Those involved in airplane observation and its transition to the new radiosonde method were not only concerned with the seemingly well-defined objective of obtaining more weather data as quickly as possible. They also included in their frame of evaluation questions such as who should do the work for whom and why, how pilots could execute data collection reliably, and even whether ‘robots’ should replace humans for this work. The historical actors’ use of the term ‘robots’ for the radiosonde makes it possible to consider this episode as a case of ‘automation’ – understood as ‘the use of electronic or mechanical devices to replace human labour’ – although the latter term was not yet used widely at the time.\(^5\) One may ask which part and how much of the observation work the radiosonde was thought to automate and in what sense this automation was regarded as more desirable. The term ‘robots’ also highlights the importance of human labor in the competing method of airplane observation. Despite the self-recording capacity of the measuring instrument itself, the novel environments in which the instrument functioned – the transient upper-air and the new working relationship between meteorologists and pilots – required physical, technical, managerial, and rhetorical actions from those involved in the observation project. It is through a detailed description of this human labor that the meaning of ‘robots’ in weather observation can be better understood.

Upper-air observation is a scientific endeavor to capture the turbulent, chaotic continuum of air into some fixed, legible forms, which makes it a good example to discuss what Bruno Latour called ‘cycles of accumulation.’\(^6\) Like the Portuguese carracks sent out to ‘bring the lands back with them’ by drawing maps and collecting specimens, meteorologists have sent kites, balloons, or airplanes up to the air to bring the atmosphere back. In performing this daunting task, scientists first chose particular types of data – air temperature, pressure, and humidity – as the targets of measurement and analysis, and then attempted to establish useful information from the air through various technical and managerial apparatuses, in other words, by fixing both instruments and people. Collecting weather data demanded ceaseless attention, because small disturbances in various segments of each cycle – failure to reach high altitude, instability of the instrument as a result of strong wind and vibration, or even a crash of a sounding airplane – could render any inscription impossible or useless. Therefore, rather than sitting comfortably on the ground and waiting for the data to flow in, meteorologists were often frustrated by their failure, owing to natural, technical, or human causes, to maintain complete control of the observation activity. Air, as a subject of organized study, tended to slip from scientists’ grasp because of its transient nature and the tendency of kites, balloons, airplanes, and pilots to resist remaining fixed, literally and figuratively.
Recording in the wind

The increasing use of airplanes after the First World War demanded more accurate weather forecasts for aviation in the USA. The forecasts for airplanes had to be based on several types of weather information from the upper-air, such as wind direction and speed, air temperature, pressure, and humidity. The study of these upper-air weather conditions came to be called ‘aerology’ and was understood as a sub-discipline of meteorology. During the 1920s, the Army, the Navy and the Weather Bureau cooperated in aerological works such as upper-air soundings, weather forecasts for aviators, or the training of aerological personnel.\(^7\)

Despite the earlier wishes of meteorologists like Bjerknes, however, the airplane was not yet considered as an effective tool for observation in the early 1920s. As Charles Marvin, the Chief of the Weather Bureau, testified before the Congress in November 1922, ‘very little use has been made up to the present time of airplane for taking observations in the free air.’ The advantages of using an airplane would have been numerous: higher altitude than kites, better predictability than balloons, and the speedy retrieval of the data. However, flying an airplane with a recording instrument was deemed more expensive than flying kites or sending up balloons. Moreover, the instrument on a moving airplane was unable to record the actual wind speed, which was one of the important weather factors for aviators. Marvin believed that the Weather Bureau could ‘get better results at less cost’ with balloons and kites.\(^8\) The great technological marvel of the day, the airplane, was considered inferior to kites and balloons for the purpose of upper-air sounding.

Indeed, most upper-air observations used kites and balloons until the early 1920s. As of 1922, the Weather Bureau was maintaining six observation stations that used both kites and balloons and there were nine additional stations only for ‘pilot balloon’ observation. In a kite observation, the meteorologist attached a meteorograph to the kite and flew it to the height of about two miles.\(^9\) A typical meteorograph contained a thermograph, a barograph, and a hygrograph that measured air temperature, pressure, and humidity, respectively. A mechanical pen recorded the continuous change of each element on a rotating cylindrical surface. When the kite was pulled back to the ground, the recordings inside the meteorograph could be retrieved and analyzed. A pilot balloon was introduced in 1918 for the measurement of wind direction and speed. After the small rubber balloon filled with hydrogen (and later with helium) was launched with the pre-calculated ascension rate, a ground observer tracked its movement by looking through a theodolite, which enabled the observer to calculate the position and speed of the balloon, and accordingly, the wind direction and speed. Another type of the weather balloon was the ‘sounding balloon,’ which was sent up with a meteorograph to record temperature, pressure, and humidity. A parachute was attached to the meteorograph, so that the instrument could return to the ground safely after the balloon burst at a high altitude. Unlike kites and pilot balloons that gave necessary data within several hours, the information recorded by sounding balloons could be retrieved only when a good-natured person discovered the meteorograph and sent it to the Weather Bureau, often several months after the flight. These three methods – kites, pilot balloons, and sounding balloons – were extensively used in the USA throughout the 1920s.\(^10\)

The Weather Bureau and the Army Signal Corps made the first airplane sounding in 1918, and the Navy Aerological Section started its first airplane sounding in 1923 at the San Diego Naval Air Station. As Marvin’s negative comments suggest, however, the meteorologists had much difficulty in improving the efficacy of airplane observation. Making weather recording instruments function properly in the upper-air required a lot of work. In each flight, the meteorograph (also called ‘aerograph’ in the Navy) was attached to an
airplane and flown into the upper-air to obtain weather information. A serious concern for meteorologists was how to reduce distorting external influences upon the measuring instrument: the enormous speed, vibration, and heat caused by airplanes. Quite unlike kites and balloons, an airplane was a huge machine with a hot, growling engine. It moved at an unprecedented speed in the upper-air and so did the meteorograph attached to it, posing a serious challenge to meteorologists and engineers, who struggled to make the meteorograph a reliable inscription device, often without much success (see Figure 1).

From the beginning of the airplane sounding program, the Navy’s aerological personnel spent much time and energy in devising the best method for ‘exposing’ or ‘suspending’ the
aerograph on the airplane. The basic principles of aerograph exposure were to eliminate vibration by the motor, to avoid heat from the motor and its exhaust, and to prevent the aerograph from damaging the airplane and causing a disaster. At the Naval Air Station in San Diego in 1925, an observer sitting in the rear cockpit held the aerograph by hand ‘well above his head,’ trying to keep it from exhaust blast and to minimize vibration. The aerographer in San Diego wrote to Lieutenant Francis Reichelderfer in Washington, DC, who was in charge of the Navy Aerological Section, ‘It may, on first thought, seem that the instrument should be slung but in want of a satisfactory way of slinging the instrument, we think this is the best way to get the data.’ Reichelderfer did not endorse the method used in San Diego, but even he had not established the best method yet. Reichelderfer once tried to use screws to fix the aerograph to a plane’s fuselage or wings. While he could achieve firm suspension by screws, however, the recorded traces appeared indistinct due to the vibration of the plane. Writing in April 1925, Reichelderfer had to acknowledge that the exposure methods in use were ‘not entirely satisfactory.’

In order to maintain consistency in weather data, the Aerological Section headquarters in DC could not allow locally improvised methods of exposure. Unable to impose a reliable solution, however, the headquarters had difficulties in overseeing daily practices at the local station in San Diego. Frustrated by the objection from the headquarters, the San Diego commanding officer reported to the Chief of the Bureau of Aeronautics in May 1925: ‘Experiment has proven that, with present methods of suspension, the collection of any great amount of data is impossible. No method of suspension has been found whereby the vibration of the plane’s motor does not affect the recording elements of the aerograph.’ In reply, the Bureau notified the San Diego station of its on-going experiments, which had been ‘successful in eliminating most of the effect of vibration.’ As the Bureau became quite optimistic about the new development, the San Diego method was strongly discouraged again. The ‘personal error’ in the method would be unacceptable, because it tended to vary with ‘the height to which the observer held the instrument, the length of the observer’s arm, etc.’ Not just a local deviation from the central control, this method was also dependent on unpredictable personal variations.

After some experiments at Anacostia, DC, the Bureau of Aeronautics became confident in its method and wanted other naval stations to adopt it. By August 1925, the Bureau of Aeronautics agreed with the Weather Bureau on their answer to the survey requested by the International Meteorological Committee: ‘The meteorograph is suspended by means of bungee (rubber) cord and wire to the inside of an iron frame or cage, secured to the top, center, of the upper wing of the plane.’ The San Diego station, however, continued its method of carrying the aerograph by a person sitting in the cockpit until January 1928, when it finally accepted the method of exposing the aerograph between the upper and lower wings. Dean Blake of the Weather Bureau office in San Diego could now report that ‘undoubtedly, the wing exposure, which is away from heat from the engine, is much the best’ (see Figures 2 and 3).

It seems that most naval stations conducting aerological flights adopted the same method of exposure by 1928. It did not mean, however, that the Navy Bureau of Aeronautics was now completely satisfied with the method in use. The problem of aerograph exposure did not find a thorough solution until the mid 1930s, when the daily airplane observation program officially expanded on a national scale. In May 1931, the Bureau of Aeronautics was still seeking ‘a standard type of suspension for aerographs ... with a view toward eliminating many errors ... due to vibration and incorrect ventilation.’ Even in January 1935, the Bureau was ‘attempting to develop a standard method of mounting aerographs on naval planes.’ Ten years, it seems, was not a long enough time to devise a
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satisfactory method to carry an aerograph on an airplane. The aerograph had to be attached to the airplane as tightly as possible, but at the same time it must be kept away from the influences of the airplane. This kind of dilemma had not existed in the previous methods of kites and balloons. The airplane was a very powerful probe into the atmosphere, but was also a very unstable one; the carrier of the instrument was actually the biggest source of recording errors. In other words, the very act of placing the instrument into the object of measurement was creating disturbance in the outcome; it was almost impossible to measure nature in its pure state. Although the same could be said of kite and balloon observation, the heat and vibration of the airplane was incomparably more difficult to deal with.

Another technical problem that concerned meteorologists and engineers was how to obtain reliable meteorographs and test them for realistic operating conditions, and this was not resolved with perfection until the 1930s, either. For instance, because of the high speed of the airplane, the temperature-recording element inside the meteorograph – thermograph – always showed certain amount of time lag between the actual outside temperature and the temperature being recorded on the device. The difficulty in designing a satisfactory temperature recording unit consisted of the basic fact that, whereas thermometers at ground level recorded the temperature as a function only of time, the temperature during an aerological flight varied not only with time but also with three-dimensional location.  

Tests conducted at the Meteorological Division of the Massachusetts Institute of Technology (MIT) reveal the seriousness of the thermograph problem. Karl O. Lange, who came from Germany to work on MIT’s aerological soundings, found it difficult to keep the temperature lag small enough. In a test at the air speed of 63 miles per hour generated by the MIT wind tunnel, two Friez type aerographs, which were widely used by the Weather Bureau and the Navy, were found to reach the equilibrium state when the deviation from the actual temperature was as high as 3.1°C and 2.3°C. This meant that, ‘without the application of
corrections,’ the data ‘may frequently differ from real conditions and not be comparable among themselves.’ One immediate recommendation to prevent the ‘disastrous effect of lag’ was to have the airplane climb very slowly near the ground, expecting the temperature difference to decrease. This measure would not be sufficient, however. The design of the instrument itself had to incorporate the requirements to minimize temperature lag during the flight.24
Several design features were taken into consideration to solve the lag problem. Researchers at MIT first found that the lag became smaller as the thickness of the bimetal strip decreased, which meant that the bimetal should be ‘as thin as possible.’ At the same time, the bimetal strip must not be too thin and had to maintain a certain degree of stiffness, because it needed to withstand frictions from the recording pen and the mechanical gears. The most important factor in the deformation of the strip, however, was the ventilation current inside the meteorograph. Tests showed that ‘low ventilation speeds permit the use of weak strips of small lag.’ It was also known, however, that ‘strong ventilation in itself tends to decrease the lag,’ which made the relation between the ventilation speed and the temperature lag even more complicated. More tests followed at the MIT wind tunnel with air speeds ranging from 28 to 77 miles per hour. Although it was confirmed that higher ventilation air speed decreased the lag within certain range, researchers also found it ‘evidently impossible’ to establish a single formula that would work for all conditions. Combining many factors above – thickness, stiffness, ventilation speed, etc. – the researchers finally concluded that ‘the lag can be kept down by making the bimetal as thin as possible and at the same time cutting down the ventilation speed to a corresponding extent.’

Carl-Gustaf Rossby, a Swedish meteorologist in charge of the meteorological program at MIT, became confident about its test results. In his letter to Harry Guggenheim, one of the great benefactors of aeronautical research, Rossby wrote that the MIT group had ‘completely succeeded in eliminating vibrations of the instrument.’ Rossby did not expect, however, that many other airplane sounding stations would meet the standards that his team had established. Such a rigorous process of testing and calibration could not be guaranteed at most local stations. Even when the meteorograph was properly tested and calibrated, as Lange pointed out, it still had to ‘stand the mechanical stresses during the flight, harsh treatment by inexperienced personnel and exposure to all kinds of weather.’ Rossby thus regarded the weather records at other stations not so reliable. ‘In comparison with this [MIT] record,’ he wrote to Guggenheim, ‘most of the routine data collected by, for instance, the Navy, look as if they had been painted with brushes.’ As Rossby’s remarks suggest, the scientists and engineers inside the laboratory could not exert full control on the actual practices of data inscription at scattered local sites and up in the air.

**Begging for a flight**

A reliable instrument and a secure method of its exposure were not the only concern in the airplane sounding. Also required were an airplane and a pilot that would take the instrument into the upper-air. In fact, the procurement of planes and pilots constituted a very important part in implementing the airplane observation program. The weather pilots were not a homogenous group. Some of them were military pilots in the Army and the Navy, some others were commercial pilots who were paid for their weather work, and still others were those who might be called research pilots, associated with universities like MIT and the California Institute of Technology. Despite the differences among them, however, all of them played a role in gathering weather information. The dependence of meteorology on aeronautics, which Bjerknes had foreseen in 1909, turned out to be the dependence of meteorologists on these pilots. Hence, the newly emerging relationship between meteorologists and weather pilots needs to be considered seriously, for it affected the ways in which the meteorological inscriptions were made and the meteorologists discussed the advantages and limitations of different observation methods.
When the Navy Aerological Section attempted to launch aerological flights at more stations in the mid 1920s, many aerographers often had difficulty in securing planes and pilots. Aerological flights were often prevented simply because there were no planes available, a situation that did not make much sense to aerographers. One aerographer at Pensacola Air Station reported to Lieutenant Reichelderfer in DC, ‘My aerograph pilot is busy with bombing so we have not started yet.’ Sometimes the situation became worse, and Reichelderfer received letters containing desperate statements from local aerological personnel:

I doubt if I will ever be able to make daily flights here, the flying facilities of the station are being taxed to the limit to take care of the student aviators and they will never look with favor upon a daily aerograph hop.

Unless an official order was made, most naval aviators had little incentives to help aerological personnel in their stations. Without cooperative and regular carriers, the recording instrument was of no use and the upper-air weather observation was simply not possible.

Where did this indifference, reluctance, and even hostility toward the aerological flights come from? It cannot be said that pilots were not interested in having good weather information for their flight. Bad weather had always been a critical factor in flight accidents and pilots did want to know about the weather before they took off. Moreover, pressure for regularly scheduled flights was about to build up in the civilian sector, especially with the passage of the Air Mail Act of 1925 and the Air Commerce Act of 1926, which heightened the need for better weather forecast for aviation. Certainly, military aviators were no less appreciative of weather information. The Army and the Navy, for example, provided active support for an experimental weather reporting system for the model airway between San Francisco and Los Angeles, which was organized in 1928 by the Daniel Guggenheim Fund for the Promotion of Aeronautics and used six pilot balloon stations. Obtaining weather data with their own planes, however, was a different matter. Given that most pilots in the 1920s were not proficient in flying by instruments under low-visibility conditions, making regular weather flights to the upper-air was not an easy task, whether or not the pilots were willing to do so. Upper-air sounding flights could put the pilot’s life at risk, especially in bad weather.

The risk of regular upper-air flights, however, does not fully explain the Navy aviators’ sentiment expressed in the quotes above. One contextual explanation may then consist in the delicate relationship between pilots and meteorologists as emerging professional groups. Pilots’ need for weather forecast did not always translate into hospitable attitude toward weather personnel. Promoting the significance of their field in the new aviation age, aerologists always emphasized their contribution to aviation safety and often attributed an airplane crash to the ‘lack of liaison between pilots and aerological office.’ They argued that pilots should not trust their own judgment on the weather and should instead seek advices from those ‘specially trained in aerology.’ For pilots, however, this argument implied their dependence on non-pilots in making decisions to fly or not to fly, a status that could threaten the pilots’ control in flight. Hence, as Reichelderfer wrote in 1925, ‘any meteorologist who is so tactless as to say before an aviator that flying is largely dependent upon weather is likely to be forced to put on the verbal sparring gloves to defend his position.’ Aerologists claimed themselves to be expert advisors to pilots, but pilots were not always willing to listen.
Navy aviators’ unfriendly attitude to aerologists intensified as it combined with the line-
staff antagonism in the Navy. Line officers in the Navy refused to admit that the aerological
duty needed specialization separated from general line duties. When the Bureau of
Aeronautics proposed a postgraduate course in aerology and considered creating a status of
officers ‘for aerological duty only,’ some line officers expressed vehement opposition. ‘It is
to my mind entirely the wrong way to go about it,’ wrote Captain Steele at the Lakehurst
Air Station in his letter to Reichelderfer. For him, the aerological work could be done better
by ‘a number of officers in general service and especially in aviation interested in aerology’
than by the ‘limited number of officers trained in aerology.’ Steele believed that the aerol-
ogy specialty was being created for those Navy officers who feared the general line duty
aboard battleships. He even suspected that Reichelderfer was one of them. ‘I wonder,’
Steele wrote to Reichelderfer, ‘whether you have considered your future in such a position
[aerology only]. It does not look very bright from this point of view.’

Infuriated by the letter, Reichelderfer set himself to defend aerology and aerologists against
the line officers. ‘It is fallacious,’ wrote Reichelderfer in a memorandum, ‘to believe that an
officer can acquire the necessary expertness in aerology without interruption to the usual tour
of regular line duties.’ Since the aerological duty required several years of hard work and ‘an
inclination toward scientific study,’ Reichelderfer believed, the officers longing for a regular
line career would soon find the aerological work ‘irksome.’ Thus, the new duty was suitable
for motivated officers who were prepared to study aerology ‘indefinitely if necessary.’

In another memorandum, Reichelderfer stressed his point that the so-called ‘real naval officers’
on the line duty were not ‘omniscient super-men’ and that their ‘[fetish] for versatility against
specialization’ could undermine their ‘real mission.’ By contrast, naval aerologists, through
their dedicated work for aviators, were so sincere about their ‘real mission’ as to ‘lose the
advantages for promotion and selection, as line officers, which accrue to naval aviators.’

Given this underlying tension between the aviators as line officers and the aerologists as
specialized staff, the dilemma of aerologists was that they nevertheless had to rely on pilots
for upper-air soundings. There was a peculiar contrast between the apparent insignificance
of pilots’ technical function and the undeniable centrality of pilots in airplane weather
observation. Viewed one way, they may be called ‘invisible technicians,’ since they simply
carried the instruments for meteorologists. From a different perspective, however, they were
highly skilled professionals on their own and no weather data could be obtained from the
upper-air without them. Just as pilots did not like losing the control of flight to aerologists,
the excessive dependence on pilots was not desirable for many aerologists. Although
aerologists tried to enlist aviators as their ‘partners in creating and advancing the science of
aeronautical meteorology,’ they also wanted to maintain their control in meteorological
work. C. LeRoy Meisinger of the Weather Bureau, for example, emphasized that the
airplane observation should be implemented ‘under the supervision of trained meteorolo-
gists.’ In the Navy, some aerologists argued for the flight training of aerographers, hoping
to decrease their dependence on pilots. Lamenting some pilots’ ‘lack of nerve’ in turning
back owing to the bad flying weather, an aerographer in San Diego wanted to enroll himself
in a flight class, because ‘an aerographer would never have had the nerve to admit that he
didn’t have the nerve to go thru!’ With Reichelderfer’s ‘strong recommendation,’ he
seems to have finally got into a flight class.

‘Flying weather man’
Although technical problems and personnel issues did not dissolve completely, by the early
1930s the skepticism of the previous decade about airplane sounding turned into general
optimism for more accurate forecasts and better aviation safety based on the airplane sounding data. Now, the kite system began to seem 'slow and expensive, requiring the maintenance of large fields, a squad of men and expensive housing facilities.' Moreover, kites highly depended on weather conditions; flying a kite was prevented even by a very calm weather, let alone by stormy conditions. The ever-increasing presence of electrical power lines also made the use of kites undesirable. The most serious trouble with the kite observation was the danger it posed to airplanes in the air. Marvin, still the Weather Bureau Chief, deemed the kite's steel wire 'very hazardous,' which made the kite observation 'so objectionable' to be used in areas dense with airplanes. By contrast, as a New York Times writer noted, the airplane observation was 'free from all these defects.' An airplane sounding could easily be made on a calm day, and it took less time. In addition, the aviator himself could contribute by observing the weather situation during the flight. The airplane was now regarded superior to the kite for securing the upper-air information.

In July 1931, the Weather Bureau commenced its own airplane soundings by making contracts with local aviation companies at Chicago, Cleveland, Dallas, and Omaha. The aviation companies provided pilots and planes, while the Weather Bureau furnished meteorographs as well as personnel to mount the instruments. Two years later, on 30 June 1933, the Weather Bureau closed down the last kite station at Ellendale, North Dakota. Beginning on 1 July 1934, the Weather Bureau consolidated and reshaped the airplane sounding program in close cooperation with the War Department and the Navy Department. The War Department agreed to make airplane soundings at seven airfields around the country. The Navy would also make daily airplane soundings at several air stations. The Weather Bureau made contracts with six commercial operators mostly at places where the War and Navy Department did not cover. In addition to these, MIT and the California Institute of Technology were expected to make similar flights in Boston and Pasadena, respectively.

This expansion of the airplane observation program in 1934 was based on the recommendations by the special committee of the Science Advisory Board, which President Roosevelt had appointed in July 1933. The main point of the recommendations was that the Weather Bureau needed to adopt the European air mass analysis for the weather forecasting in the USA. In order to import and apply the new theory of air mass, a considerable amount of reliable data of the American atmosphere had to be supplied, which required the improvement of the upper-air observation program by more airplane soundings at more stations. An enhanced appreciation for the science of meteorology helped create a more systematic cooperation among the Weather Bureau, the Army, and the Navy for a new weather observation program focused on the airplane method. As mentioned earlier, Bjerknes, the pioneer of the new meteorological theory, understood clearly the crucial role of airplanes in the development of modern meteorology. Indeed, Rossby at MIT wrote to his former teacher Bjerknes in 1932 asking for his letter of support for the MIT's aerological flight project, which was then suffering from a lack of funding. The change in the theoretical concepts on the one hand and the change in the instruments and methods of observation on the other were closely associated. Thus the airplane observation now became 'the most important step in the development of the air-mass analysis program.'

Continuing the cooperation with the military and also making commercial contracts, the meteorologists at the Weather Bureau tried to establish their control in the upper-air observation by making concrete specifications for the weather pilots. As the special committee of the Science Advisory Board stated, the Army and Navy pilots were expected to make soundings 'in accordance with Weather Bureau instructions and as a definite routine.' The instructions manual prepared by the Weather Bureau defined an airplane observation flight
in very specific terms: ‘A “flight” will consist of an airplane ascent (the airplane being instrumentally equipped as required by the contract) made at a rate not greater than 1500 feet per any five minute period.’ The rate of climb was restricted in order to prevent the time lag in the recording elements. Moreover, the flights had to be made daily including Sundays and holidays, and the Weather Bureau wanted the flights to begin at 4 a.m. and to reach 16,500 feet above sea level. Since only the data made during the ascent were used, the pilot was told, once he reached the required height, to ‘level off for one minute and then return to the ground as rapidly as practicable.’ The pilot was also required to report his observations during the flight, which was a measure of whether he was ‘performing satisfactory service.’

The pilots under contract were remotely managed by the meteorologists in Washington, DC through the work of local Weather Bureau personnel. In order to keep an eye on the pilots, the Weather Bureau demanded that the official at the observation station report to the Central Office about any frequent violations by pilots. Much attention was given to the specifications such as ‘the proper reporting of pilot’s notes, maintaining and using two-way radio, the carrying of passengers, etc.’ The pilot was strictly forbidden to carry ‘unauthorized passengers,’ whether free or paid, and the Weather Bureau deemed it ‘especially desirable that this regulation be enforced.’ The officer in charge was also told to report if he felt ‘unable to get better cooperation’ from pilots, so that the Central Office could make appropriate actions.

The pilots as employees were in constant surveillance by the meteorologists as employers.

The most direct means of control by the Weather Bureau was a strict payment policy for the civilian pilots employed for weather work. The first contract with a Chicago pilot in 1931 stipulated that he would be paid US$25 if he reached 13,500 feet. There was a 10% bonus for each additional 1500 feet, which was an ‘incentive’ for reaching ‘the greatest possible height.’ By 1938, the reference altitude was increased to 16,500 feet and the bonus policy for reaching higher than the specified altitude disappeared. There was instead a deduction policy, according to which a pilot would be paid ‘on a percentage basis’ if he reached less than 16,500 feet. He would get no payment if the altitude was lower than 20% of the requirement. In case of a failure to reach the minimum height, the pilot could make another flight during the same day and was paid for the higher altitude of the two flights.

This kind of piecework contract by the Weather Bureau could prompt the pilots to ‘take the risk’ to ascend higher, and the Weather Bureau Chief Willis Gregg (Marvin’s successor) knew it well when he said at the House Committee on Appropriations that ‘unquestionably [the risk] enters into the contract rate or price they ask.’ At least with those pilots under direct contract, the Weather Bureau was acting as a manager who understood well Frederick Taylor’s claim that ‘plenty of workmen can be found who are willing to work at their best speed, provided they are given this liberal increase in wages.’

No less care was taken by the Weather Bureau to ensure the regularity of flights. The Central Office required immediate reporting from the local official in case of the contractor’s failure to reach 16,500 feet without legitimate excuses ‘on more than three days during any 30 consecutive days,’ so that the Bureau could try ‘to procure service in the open market.’ In consequence, the Weather Bureau evaluated the weather flights’ regularity as ‘most gratifying,’ especially when compared with the previous kite observations. It is noteworthy, however, that the flight regularity was generally higher at the stations under direct contract with the Weather Bureau than at the stations maintained by the Army, the Navy, or MIT. For example, Lange at the MIT Meteorological Division claimed that the 100% regularity was not compelled there, since ‘the value of an individual meteorograph ascent is not to be compared with the value of human life or even a serious risk of plane and
The enhanced regularity of airplane observation in general was an achievement by careful management rather than a natural consequence of the technical superiority of airplanes over kites. Whether or not 100% regularity was achieved, each weather flight to the upper-air constituted one small ‘cycle of accumulation’ of weather information. According to Latour, the purpose of such cycles is to obtain inscriptions of nature that are made into ‘immutable mobiles.’ In the upper-air observation, the meteorologists tried to capture the transient air onto lined data sheets, which would be easily circulated across individuals and institutions. The case of the airplane sounding program illustrates that making the inscriptions ‘immutable’ and ‘mobile’ required much more than just automatic, self-recording instruments. The very fixity, or ‘immutability,’ of the inscriptions – here, the traces of temperature, pressure, and humidity – was highly predicated upon the reliable transportation between the upper-air and the ground station. The weather information was not fixed at the moment of recording in the upper-air. Since they were usually the markings on a smoked cylindrical surface, the traces were always subject to erasure, for instance, simply by wiping off the smoke. Only after the airplane landed safely with the meteorograph intact could the inscriptions be made ‘immutable’ by applying the chemical ‘Fixatif.’ It was because of this dependence of the inscription’s fixity upon its carrier – the airplane and the pilot – that the airplane sounding flight had to be a disciplined one with the regulated rate of climb as well as the requirement of immediate descent. ‘Immutability’ and ‘mobility’ were not the qualities inherent in the medium or mechanism with which the inscriptions were made, but rather consisted in the physical and managerial work by pilots and meteorologists (see Figure 4).

What did the pilot do actually, then, to make a safe transportation of the weather data between the upper-air and the ground and what was the experience of an observation flight like? One might think that the sounding flight was rather monotonous because the pilot had ‘nothing to do but get his ship up to 16,500 feet and get back down safely.’ Indeed, ‘the prop’ of the MIT plane was ‘set to give 100 per cent of power when climbing,’ unlike the ‘stock airplanes’ whose maximum speed was obtained at level flying. However, the upper-air observation flight posed a serious risk to the pilot. The extremely cold air was the first threat. The pilot, also called the ‘flying weather man,’ thus needed to put on ‘a mountain of clothing,’ which included ‘a heavyweight suit of woolen underwear,’ ‘a double heavy knitted cap,’ ‘a long rag of white silk,’ and ‘a pair of giant fur lined gloves, with finger mitten attached at the back.’ To prevent another danger of suffering from ‘the rarefied air of such heights,’ some pilots took their pets as indicators of life-threatening conditions. When a dog, a cat, or a squirrel began to ‘droop,’ the pilot would ‘nose the ship down.’ The requirement to descend ‘as rapidly as practicable’ could be dangerous, too. For instance, when an Army pilot was descending at two hundred miles per hour, the ‘excessive vibration’ due to the strong wind blew away the meteorograph from the airplane wing. Although the detached instrument did not kill the pilot or damage the airplane, the pilot suggested that the descent instruction be changed.

Airplane weather soundings did cost human lives, not to speak of planes and instruments. Flights in inclement weather often ended up with forced landings, some of which could be fatal. During the year 1937, there were eight crashes and six pilots were killed. In addition to the pilots, some observers and passengers were also killed or seriously injured. According to one estimate, a total of 12 people were killed from the beginning of the practice in the early 1930s to the year 1938. The loss of personnel and planes from weather flights caused much concern to those participating in the program, especially the Army. On 26 January 1938, the Secretary of War, Harry Woodring, wrote to the Secretary of Agriculture to
Figure 4. A meteorogram from an airplane sounding in Omaha, Nebraska, on 9 March 1934. Source: *Monthly Weather Review* (April 1935). Courtesy of NOAA.
notify his decision to discontinue the weather flights. ‘The War Department has conducted these flights,’ Woodring emphasized, ‘at a considerable sacrifice, involving loss of lives of Air Corps personnel, diversion of personnel and equipment from military training, and the destruction of valuable equipment.’ Faced with fatal losses and other changes in the Army, however, the War Department could no longer find justification for the weather work that endangered its pilots and planes. The Army’s decision to discontinue the weather flights was also influenced by the fact that new monoplanes that were replacing old biplanes were not suitable for attaching meteorographs to the wing. Moreover, the Army was aware of the new radiosonde sounding method, which was expected to replace the airplane soundings in the near future.

‘Robot observer’

Recognizing the risks involved in the weather flights could generate a version of scientific heroism and in the media there was some portrayal of weather pilots as heroic figures working for science and public good. In the coverage of the MIT’s air station, the Christian Science Monitor reporter described an MIT-affiliated pilot, Lieutenant Henry Harris, as one of the ‘scientists who labor quietly, earnestly, in good weather and bad, to serve industry, to advance human knowledge, that the world may be more safe, more happy, more in harmony with the great “Upstairs.”’ John Riley of the Weather Bureau also highlighted pilots’ hard work ‘in the interest of aviation and a better service.’ ‘The weather pilot, like the air mail pilot of an earlier day,’ he wrote, ‘carried on in spite of storms and darkness.’ When the time finally came for him to bid ‘farewell to airplane weather soundings,’ therefore, he felt obliged to ‘pay tribute to the pilots.’

Why, then, did he finally bid farewell to the weather pilots? As historian Naomi Oreskes wrote, in order for a scientific work to be deemed heroic, the work needs to be physically demanding and those who do the job must seem irreplaceable. Once the work becomes ‘routinized,’ however, it is no longer considered heroic and the practitioners become ‘interchangeable.’ As the Science Advisory Board emphasized, the whole point of the airplane observation program was to make it a ‘definite routine.’ Unlike the much-praised heroic endeavors of polar expeditions or stratosphere explorations in the same era, the daily weather flights were not supposed to have any spectacular quality. Also, the human presence in the upper-air was required not for any kind of symbolism but merely for technical reasons; the recording instrument needed a carrier for each round trip. Although some may have regarded weather flights as courageous, laudable activity for science, these instrument carriers were eventually replaceable when it seemed possible to do so.

By the end of the 1930s, a new device called ‘radiometeorograph’ came to take over the pilots’ job. The development of the radiometeorograph was hailed as ‘the beginning of a new and very important epoch in weather service.’ In the USA, the process involved many institutions including the Navy Bureau of Aeronautics, the Navy Bureau of Engineering, the Bureau of Standards, the Weather Bureau, the Blue Hill Observatory at Harvard, the California Institute of Technology, and some scientific instrument companies such as Julien P. Friez & Sons. Some early models of the radiometeorograph were attached to airplanes for soundings and even reported as ‘new airplane devices,’ but it became clear soon that the new device would be suitable for use with small balloons. The key feature of the new device was that, attached to an ascending balloon, it would transmit, by means of radio signals, the three types of weather information to the ground receiving station. Variations in temperature, pressure, and humidity would change the characteristics of the electrical circuit, which would then generate radio signals with varying frequencies. As continuous
changes of the air were sampled and translated into radio signals capable of traveling through the air without a human carrier, the pilots who had physically delivered the analog traces of the air did not seem necessary any longer. After series of tests, the radiometeorograph began to be used for daily soundings in 1937. In 1938, the Weather Bureau as well as the Navy adopted a new official name for the radiometeorograph: the ‘radiosonde,’ a term originally coined by French scientist Robert Bureau in 1931. At the Weather Bureau stations, the radiosonde entirely replaced the airplane sounding during the fiscal year 1940.  

The replacement of airplane sounding by the radiosonde, however, was not straightforward. The arguments for the adoption of the new device could be summarized as follows: ‘The new method will give three or four times the altitude, comparable accuracy, in half the time, at less cost and is fairly independent of weather conditions.’ There was no question that the radiometeorograph could reach much higher than the airplane or that the data by radio could be processed faster than the previous method, and it was also acknowledged that the airplane observation would never achieve ‘perfect regularity’ because of its dependence on weather conditions. But perceived issues of accuracy and cost complicated the choice.

First, why did those involved claim only ‘comparable accuracy’ for the radiometeorograph? Part of the answer was that there was no absolute reference against which the accuracy of recording could be judged. The data from a radiometeorograph had to be evaluated by making a simultaneous airplane sounding and comparing the two results. The tests could only show, therefore, that the radiometeorograph result was ‘as accurate as those obtained by airplane soundings’ or that the two recordings ‘showed very close agreement,’ but even proving the agreement between the two was not always easy. When, in a test at MIT in 1937, there were found ‘consistent discrepancies’ over 2°C between the two temperature recordings, the testers decided to recalibrate the airplane meteorograph, suggesting the possibility of some changes in the instrument since the last calibration. Only after the data were ‘recomputed’ using the new calibration did the results show ‘excellent agreement.’

Moreover, the legitimacy of comparing the two methods was open to question. Reporting on another comparison test, L.T. Samuels of the Weather Bureau cautioned the reader to consider ‘a number of factors’ before drawing a conclusion. The airplane meteorograph and the balloon radiometeorograph followed different paths in the air, were sometimes launched with time difference between the two, and had different rates of ascent and recording lags. All these factors could undermine the reliability of comparison. Although he did not doubt the need to adopt the new device, Samuels thought that attaching a non-radio meteorograph to the same balloon would make a better comparison than making a separate airplane observation. In 1940, the Bureau of Standards at last disapproved the use of airplane sounding as ‘an exact check’ for the radiosonde, explaining that ‘the airplane generally travels through the air mass whereas the radio sonde travels with the air mass.’ In other words, it was not self-evident whether the radiosonde was a more ‘accurate’ recording device than the meteorograph attached to an airplane.

Second, the argument for the radiosonde in terms of its cost advantage depended on how they calculated the total cost of an upper-air sounding. According to the Navy’s estimation in 1938, the total cost of one radiometeorograph flight was $30.25, while the cost of each airplane sounding was $25. This additional cost of the new method, however, could be ‘justified’ by other advantages; in addition to higher regularity and altitude, ‘there will be no chance of injury to personnel or damage to the airplane.’ In other estimates as well, the Navy Aerological Section always claimed that the increased cost would be compensated by ‘less frequent use’ or ‘non use’ of airplanes. Likewise, Major General H.H. Arnold, the
Chief of the Army Air Corps, emphasized the cost of six airplanes that crashed during weather flights, $20,000 apiece, in addition to the several lives lost. ‘The radiometeorographs costs [sic] only $25 or $30 apiece,’ he said, ‘and thus you can see the number of radiometeorographs you can buy for one airplane.’ Although the Army did not purchase an airplane solely for weather flights, the loss of an airplane was nevertheless calculated into the cost of airplane sounding.

Perhaps, then, a strong argument for adopting the radiosonde was not so much that it did better than the airplane as that it could dispense with airplanes and pilots. The major problems in airplane observation could be resolved only by removing airplanes and pilots rather than by improving their performances. First, the airplane itself was the biggest obstacle to accurate measurement. The heat, vibration, and high speed of an airplane were simply unavoidable. Second, but more importantly, pilots were human beings that meteorologists had to instruct, supervise, and pay. One might see this as an improvement from the earlier days when a Navy aerologist was ‘in the status of a beggar,’ but the human pilots continued to cause much concern to meteorologists, since they could destabilize, by being largely responsible for the ‘immutability’ and ‘mobility’ of weather inscriptions, the meteorologists’ control in the upper-air observation work. Humans were more difficult to manage than machines. Speaking in 1939 as the new Weather Bureau Chief, Reichelderfer was well aware of the advantages of the ‘unmanned’ balloon over the ‘manned aircraft.’ He said, ‘Being unmanned, [the radiosonde] involves no hazard to pilot or observer in bad weather.’ In the earlier upper-air sounding, the term ‘unmanned’ had often been used to denote sounding balloons as ‘unmanned balloons.’ In this usage of ‘unmanned,’ it is not obvious who, if anyone, was unmanned. In the case of the radiosonde, however, it was clearly the pilots, not meteorologists, who were taken out, rendering the sounding unit ‘unmanned.’ Willis Gregg, who was Reichelderfer’s predecessor, aptly captured this implication of the radiosonde when he reportedly coined a new nickname for it: ‘robot observer.’

The terms ‘unmanned’ and ‘robot observer’ that were often used to describe the new observation method performed an effective rhetorical function. They helped meteorologists frame the transition to the radiosonde method as a simple case of automation: a change from the manned (airplane-pilot-meteorograph) operation to the unmanned (balloon-radiometeorograph) one. In short, the ‘robot observer’ successfully ‘unmanned’ the pilots as the carriers of instruments. A consequence of this characterization is that one’s attention is directed exclusively to the pilots as if they were the only humans involved in the observation activity, despite the fact that the unmanning of pilots had to be accompanied by the manning of new people such as radio operators. Moreover, the description of the radiosonde as the ‘robot observer’ relegated the work of weather pilots to a sort of drudgery, which could be easily performed by automatic machines. As early as 1934 when the airplane program was well under way, a proponent of the new radio method characterized the ‘risk of life to get data’ as ‘upper air stunts,’ which might well be ‘deplored as unnecessary.’ Why would anyone bother to fly higher and higher when robots can arguably do a better job? ‘Robots are going to make Uncle Sam’s weather flights now,’ the New York Times reported in July 1938, ‘displacing aviators who brave danger daily to get data at high altitudes.’ With the introduction of the ‘robot observer,’ the role of the ‘flying weather man’ was now denied.

**Instruments, inscriptions, and identities**

In scientific laboratories or field sites as well as in manufacturing factories, robots achieve some automation by making some parts of the operation ‘unmanned,’ but rarely bring about
the so-called full automation. What is it, then, that was actually automated by the ‘robot observer’? The main functions of measuring the weather remained almost the same as the previous versions of meteorographs that had already contained the self-recording feature for a long time. Instead, the new radio instrument automated the physical transportation of data by human carriers that now seemed tedious. Given the two decades of the meteorologists’ efforts to implement the upper-air observation, however, it seems that what the ‘robot observer’ automated most effectively was the delicate ‘relationship of mutual dependency’ between meteorologists and pilots.

As historians and sociologists have shown in numerous studies of machines in factories, offices, and laboratories, an instrument often generates a socio-cultural space in which different groups of actors make conflicts and negotiations about what kinds of work should be done by whom in what manner. What the instrument does might be simple enough, such as recording air temperature, but the way it did so could have different meanings to different people. For meteorologists, the upper-air observation was about designing, testing, and calibrating instruments as well as about organizing, supervising, and (dis)qualifying people. Making inscriptions of nature and choosing particular instruments and techniques for the task required judgments and actions not only on the nature’s turbulent state but also on social relationships and cultural meanings. This seems to be a part of the reason that the strenuous effort to relate airplanes, pilots, and meteorological practice was never satisfactorily completed.

The conversion from analog traces physically attached to an airplane to invisible radio frequencies inside a radiosonde effected changes in the kinds of work performed to make observation possible, requiring different groups of people who had different skills, knowledge, and status. In the former method, a ‘cycle of accumulation’ demanded procuring a pilot and a plane, attaching the instrument to the plane painstakingly, regulating the rate of airplane ascent, stipulating strict payment policy for each flight, and finally, ensuring their fast and safe return. In this method, each act involved some measure of uncertainty. In the latter method, by removing pilots and introducing ‘robots,’ the organized system of data collection eliminated many of these technical, organizational, financial, and even life issues. In this respect, the radiosonde meant a notable break with the past practices of upper-air observation and weather forecasting. The neat image in a present day textbook, in which a meteorologist wearing a tie is ‘downloading’ the upper-air data from a radiosonde to his laptop, may be a long-term result of this change in the late 1930s.

The ironic position of pilots in the upper-air sounding and their eventual displacement by ‘robots’ seem to reflect an interesting disjunction at that time between the public perception of pilots and the upcoming changes in their piloting experiences. On the one hand, airplane pilots, combining the mastery of machinery and the courage to take risks, were heroic figures on their own, of whom Charles Lindbergh was exemplary. The two decades examined in this study were a period when ‘flying was a sacred and transcendent calling that more than justified its cost in lives’ and ‘aviators, like sports figures and actors, became celebrities.’ On the other hand, new flying instruments such as the Sperry autopilot were beginning to complicate
pilots’ heroic control in flight, anticipating the reconfiguration of a pilot’s role in the cockpit. Instrument flying, or ‘blind flying,’ had been gaining importance since the early 1930s, requiring pilots to trust instrument panels rather than their own senses. In the upper-air observation work, the pilots’ sophisticated flying skill was not appreciated by meteorologists. They were required only to go up in a manner specified by meteorologists and to come back down alive. Their labor was crucial in the scientific work, but it was readily replaceable by new labor-saving instruments. Their status in science was insecure, if not entirely ‘invisible.’

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Notes
1. Quoted in Friedman, Appropriating the Weather, 57. For the scientific work of Bjerknes, see also Friedman, ‘Constituting the Polar Front.’
2. French scientist Robert Bureau is credited with coining the term ‘radiosonde’ in 1931. DuBois, Multhauf, and Ziegler, The Invention and Development of the Radiosonde, 33. The Oxford English Dictionary (draft revision of June 2008) lists an early usage of the term in 1932, which was in an American media report: ‘For upper air research the Weather Bureau hopes to use – in addition to the airplane – a new device known as the radio-sonde.’ According to the dictionary, ‘sonde’ meant a probe or a sounding-line and was first used in the term ‘balloon-sonde’ in 1901. The US Weather Bureau and the Navy officially adopted the term ‘radiosonde’ in 1938. See Monthly Weather Review 66 (October 1938), 326; Chief of the Bureau of Aeronautics to Chief of the Bureau of Engineering, ‘Adoption of Descriptive Term for Aerological Sounding Operations,’ 8 November 1938 (National Archives and Records Administration [hereafter NARA], RG 72, entry 62, box 2539, vol. 16). Of the records at the National Archives, I used the materials in Record Groups 27, 38 and 72, which are the Records of the Weather Bureau, the Records of the Office of the Chief of the Naval Operations, and the Records of the Bureau of Aeronautics, respectively. Record Group 27 is located in the National Archives II, College Park, MD, and Record Groups 38 and 72 for pre-Second World War periods are located in the National Archives I, Washington, DC.
3. DuBois, Multhauf, and Ziegler, The Invention and Development of the Radiosonde, iv. As described well in this Smithsonian study based on its collection of weather observation instruments, much of the early invention and development of the radiosonde and other non-radio recording instruments occurred in Europe as well as in the USA. The US story is told in this essay, therefore, not to identify ‘the first in history,’ but to explore the particular ways in which the instruments were used and discussed within the US context.
4. For example, one meteorology textbook explains to undergraduate students that the radiosonde replaced kites and other types of balloons, not airplanes, and opened a new age in the study of the atmosphere. Lutgens and Tarbuck, The Atmosphere, 18–19. DuBois, Multhauf, and Ziegler (The Invention and Development of the Radiosonde, 31) also describe ‘the transition from balloonsonde [the sounding balloon] to radiosonde’ as ‘a “natural” next step in the evolution of meteorological instrumentation.’ Histories of the twentieth century meteorology mention airplane sounding programs only in passing, if they do at all. For example, see Friedman, Appropriating the Weather, 230–6; Nebeker, Calculating the Weather. Nebeker does not discuss airplane soundings, while Friedman briefly mentions it. Some institutional histories of the US


7. The US Navy established the Bureau of Aeronautics in September 1921, and created the Aerological Section under the Bureau to organize and supervise meteorological work for the Navy. Bates and Fuller, *America’s Weather Warriors*, 36. The preparation and dissemination of weather forecasts was primarily the responsibility of the Weather Bureau, but the Navy played an active role in aerological works. Although the Army Signal Corps was also involved in the aerological activity and was cooperating with the Weather Bureau, the Navy was more active than the Army in aerological observation and research. This paper deals mostly with the Navy’s and the Weather Bureau’s works in aerology in cooperation with universities such as the Massachusetts Institute of Technology (MIT). See Harper, *Weather by the Numbers*, chaps 1–2. I thank Kristine Harper for sharing her dissertation chapter with me, which was valuable for the research on this paper.

8. For kite observation, see Marvin, *Kite Experiments*; Marvin, ‘The Kite.’

11. The term ‘aerograph’ was used interchangeably with ‘meteorograph.’ Especially, the Navy used ‘aerograph’ as the official name for the instrument. Another name ‘aerometeorograph’ was also used occasionally. In this paper, I use ‘meteorograph’ and ‘aerograph’ interchangeably, depending on the institutional context in which the instrument was referred to.

12. Lindman, ‘Aerological Activities.’ Airplane soundings with meteorographs were soon expanded to other Naval Air Stations such as Anacostia, DC, Lakehurst, NJ, and Pensacola, FL. Talman, ‘Science Measures the Weather.’

13. An aerographer of Naval Air Station (NAS) at Anacostia to Francis Reichelderfer, 9 April 1925 (NARA, RG 38, entry 301, box 1, folder 1); Reichelderfer to Willis Gregg, 9 April 1925 (NARA, RG 38, entry 301, box 1, folder 1).

14. B.H. Wyatt to Reichelderfer, 3 April 1925 (NARA, RG 38, entry 301, box 1, folder 1).

15. Reichelderfer to Willis Gregg, 9 April 1925 (NARA, RG 38, entry 301, box 1, folder 1).

16. Chief of the Bureau of Aeronautics to Commanding Officer, NAS Anacostia, DC, 13 April 1925 (NARA, RG 72, entry 62, box 2534, vol. 2).

17. Commanding Officer (NAS San Diego) to Chief of the Bureau of Aeronautics, 15 May 1925 (NARA, RG 72, entry 62, box 2534, vol. 2).

18. Chief of the Bureau of Aeronautics to Commanding Officer (NAS San Diego), 25 May 1925 (NARA, RG 72, entry 62, box 2534, vol. 2).

19. Charles Marvin to the Bureau of Aeronautics, 6 August 1925 (NARA, RG 72, entry 62, box 2534, vol. 2).

22. Chief of the Bureau of Aeronautics to Commanding Officer (NAS Anacostia, DC), 10 January 1935 (NARA, RG 72, entry 62, box 2537, vol. 11).
23. One report of the tests for temperature time lag in the 1920s is found in Henrickson and Brombacher, ‘Lag of Thermometers.’
24. Lange, ‘Meteorological Airplane Ascents,’ 11–13. The operating condition was assumed to be that there was a temperature change of $3^\circ$C per minute (actual lapse rate $1^\circ$C /100 m, rate of climb 300 m/min). This report was published as vol. III, no. 2 of the Papers in Physical Oceanography and Meteorology. Part II of the report was Charles Draper’s ‘Aircraft Instruments in Meteorological Flying.’
25. Lange, ‘Meteorological Airplane Ascents,’ 17–30. Lange also made similar improvements on the other recording elements – barograph and hygrograph – inside the meteorograph.
26. Carl-Gustaf Rossby to Harry Guggenheim, 11 April 1932 (MIT Institute Archives, AC 4, box 147, folder 10). AC 4 is the Records of the Office of the President. Before joining the MIT faculty in 1928, Rossby had organized and led the experimental meteorological service for airways in California, which was funded by the Daniel Guggenheim Fund for the Promotion of Aeronautics. The creation of the meteorology program at MIT was also made possible by the Guggenheim Fund. See Hallion, Legacy of Flight, 91–100 and 218–21.
28. Rossby to Guggenheim, 11 April 1932 (MIT Institute Archives, AC 4, box 147, folder 10).
30. C.E.S. to Reichelderfer, 15 January 1926 (NARA, RG 38, entry 301, box 1, folder 4).
31. A letter to Reichelderfer, unknown date, 1925 (NARA, RG 38, entry 301, box 1, folder 3).
32. Smitherman to Reichelderfer, unknown date, 1925 (NARA, RG 38, entry 301, box 1, folder 3), italics added.
33. See van der Linden, Airlines and Air Mail; Komons, Bonfires to Beacons.
35. Conway, Blind Landings, chap. 1; Ocker and Crane, Blind Flight, chap. 1.
36. Reichelderfer, ‘Comment on Court of Inquiry in Crash October 24, 1925, San Diego, Cal.,’ 16 January 1926 (NARA, RG 38, entry 301, box 1, folder 4).
38. For the tension between line officers and staff officers in the Navy, see Douglas, ‘Technological Innovation and Organizational Change’; McBride, ‘The “Greatest Patron of Science”’? For a historiographical discussion and analysis on the ‘line-staff conflict,’ see Foley, ‘Fighting Engineers,’ 161–95. The correspondences by the Navy aviators and aerologists reveal that the ‘line-staff conflict’ persisted even in the mid 1920s.
39. George Steele to Reichelderfer, 15 February 1926 (NARA, RG 38, entry 301, box 1, folder 4), italics added. See also Bates and Fuller, America’s Weather Warriors, 37–40. For the postgraduate engineering education commissioned by the Navy, see McBride, ‘The “Greatest Patron of Science”’?
40. Reichelderfer, ‘Memo for File,’ 15 February 1926 (NARA, RG 38, entry 301, box 1, folder 4).
41. Reichelderfer, ‘Points in Lakehurst letter of 16th Feb., 1926 not considered necessary to include in Bu Aero. 1st Endorsement,’ 20 February 1926 (NARA, RG 38, entry 301, box 1, folder 4). Reichelderfer also wrote directly back to Steele, saying, ‘I am quite ready to go to sea and I fully expected to be there long before this.’ Reichelderfer to Steele, 24 February 1926 (NARA, RG 38, entry 301, box 1, folder 4).
42. Reichelderfer, ‘Distribution of Aerologists’ Flight Orders,’ unknown date (NARA, RG 38, entry 301, box 3, folder 2).
43. Shapin, ‘The Invisible Technician.’
44. Meisinger, ‘The Aviator and the Meteorologist.’
45. Albert Francis to Reichelderfer, 2 February 1925 (NARA, RG 38, entry 301, box 1, folder 1).
46. Reichelderfer to Albert Francis, 12 February 1925 (NARA, RG 38, entry 301, box 1, folder 1). Although this aerologist–pilot tension was mostly a problem unique in the military, ‘a meteorologist as a pilot’ was often considered as ‘the ideal method’ for weather observation, especially at a ‘small plane station’ like the one at MIT. At the MIT station between 1932 and 1933, most soundings were made by the pilot alone, since ‘the additional altitude of nearly 3000 feet attainable by leaving the meteorologist on the ground seemed more valuable than the contributions of a trained meteorological observer.’ Lange, ‘Meteorological Airplane Ascents,’ 4–5.
47. Associated Press, ‘Planes to Go Up Daily.’
49. Talman, ‘Science Measures the Weather.’
50. *Weather Bureau Topics and Personnel* (June 1931), 167. *Topics and Personnel* was a monthly bulletin of the Weather Bureau. Several years’ issues were bound into one collective volume and re-paginated from the first page of the first issue among them. The page numbers here refer to those of the collective volumes.
52. *Weather Bureau Topics and Personnel* (May 1934), 27. The stations were located at Fort Crockett (Galveston), TX (June–November only); Kelly Field (San Antonio), TX; Maxwell Field (Montgomery), AK; Mitchell Field (Hempstead), NY; Scott Field (Belleville), IL; Selfridge Field (Detroit), MI; and Wright Field (Dayton), OH. One local National Guard unit would also make similar flights at Spokane, WA.
53. Pearl Harbor, TH; Norfolk, VA; Pensacola, FL; San Diego and Sunnyvale, CA; Seattle, WA; Washington, DC; Lakehurst, NJ, and Philadelphia, PA. Lakehurst and Philadelphia would alternate daily.
54. Billings, MT; Cheyenne, WY; Fargo, ND; Nashville, TN; Oklahoma City, OK; and Omaha, NE. The previous contracts with Cleveland, Dallas, and other places were discontinued.
55. Anonymous, ‘Air Masses are Studied.’
56. Gregg, ‘Progress in Development.’ The committee consisted of Robert Millikan, the president of the California Institute of Technology as chairman; Karl Compton, the president of MIT; Isaiah Bowman, the president of the National Research Council; and Charles Reed, the section director of the Weather Bureau office of Iowa. On the Science Advisory Board, see Karg and Hodes, ‘Karl Compton, Isaiah Bowman’; Auerbach, ‘Scientists in the New Deal’; Genth, ‘Groping towards Science Policy.’ For the development of the air-mass theory in Europe, especially in Norway by Vilhelm Bjerknes, see Friedman, *Appropriating the Weather*.
57. Rossby to Bjerknes, 27 May 1932 (MIT Institute Archives, AC 4, box 147, folder 10). At that time, Karl Compton, the MIT President, was applying to the Carnegie Institution and the Rockefeller Foundation for grants to continue the airplane work. Rossby wrote to Bjerknes, ‘Without some help from the outside this would be impossible, since the Institute must curtail its expenditures to weather the depression. Would it be possible for you to assist us in this move by writing [to] the Carnegie Institution in support of our application? We would greatly appreciate your help since so much is at stake for us.’
60. US Weather Bureau, *Instructions*, 34.
64. US Congress House Committee on Appropriations, *Agricultural Appropriation Bill for 1938*, 162.
67. Riley, ‘Farewell to Airplane Weather Soundings.’
68. Some, though incomplete, data on the number of aerological flights at each station can be found in *Monthly Weather Review*.
69. Lange, ‘Meteorological Airplane Ascents,’ 4–6. For the first two academic years since the first weather flight in November 1931, the average regularity at MIT was 89% (varying monthly from 77% to 94%).
73. H.B.H., ‘Where the Weather Grows.’
75. E.J. Saltsman (assistant observer, Selfridge Field) to the Chief of the Weather Bureau, 10 July 1934 (NARA, RG 27, NC-3, entry 50, file no. 450.9, box 3046); M.F. Slaght (2LT, Air Corps) to Observer (Selfridge Field), 9 July 1934 (NARA, RG 27, NC-3, entry 50, file no. 450.9, box 3046).


77. US Congress House Committee on Appropriations, Agricultural Appropriation Bill for 1940, 292. This was a statement by Earl F. Ward, the Chief of Airways Operation, Civil Aeronautics Authority.


80. Riley, ‘Farewell to Airplane Weather Soundings.’

81. Oreskes, ‘Objectivity or Heroism?’ 99.

82. Willis Gregg’s statement during a broadcasting by the National Broadcasting Company on 8 May 1936 (NARA, RG 27, NC-3, entry 50, file no. 040.4, box 30).


84. Samuels, ‘Report on the Weather Bureau’; ‘Annual Report: Aerology,’ 30 June 1936 (NARA, RG 72, entry 62, box 2568, vol. 2); ‘Annual Report: Aerology,’ June 1938 (NARA, RG 72, entry 62, box 2568, vol. 2); Weather Bureau Topics and Personnel (July 1939), 231. It is noted that the radiosonde was not a device with uniform mechanism of operation. Many researchers developed various mechanisms for the radiosonde. See DuBois, Multhauf, and Ziegler, The Invention and Development of the Radiosonde.

85. Memorandum for Director, Naval Research Laboratory, 30 June 1936 (NARA, RG 72, entry 62, box 2538, vol. 13).

86. Willett, ‘Routine Daily Preparation.’ While airplanes were usually required to reach about 17,000 feet, the balloon with a radio-meteorograph could regularly ascend higher than 50,000 feet, which was a definite advantage for upper-air observation. Also, the radio-meteorograph could be sent up even under severe weather conditions when it would have been impossible to do airplane soundings.


89. Samuels, ‘Report on the Weather Bureau.’


91. For the complexity and difficulty in defining and acquiring the accuracy of technical devices (‘uncertainty of accuracy’), see MacKenzie, Inventing Accuracy, esp. chap. 7.

92. ‘Estimates – Fiscal Year 1940,’ 23 May 1938 (NARA, RG 72, entry 62, box 2539, vol. 16). The total cost of the radio-meteorograph sounding included the costs of one radio-meteorograph (US$24.00), one sounding balloon (US$2.25), one parachute (US$1.00), and 100 cubic feet of helium gas (US$3.00). The Navy classified the radio-meteorograph as ‘consumable supplies,’ since the retrieval of the instruments could not be guaranteed.

93. US Congress House Committee on Appropriations, Agricultural Appropriation Bill for 1940, 1287.

94. Francis Reichelderfer, ‘Recent Developments in Aerology’ (an address delivered before Washington Assembly of the International Union of Geodesy and Geophysics, 7 September 1939) (NARA, RG 27, UD, entry 124, box 1).

95. ‘Robot observer’ was a common name for the radiometeorograph in the press coverage. See Speers, ‘Aid to Safe Travel.’

96. See David Mindell’s discussion of ‘unmanned weapons’ where he asks, ‘Whom do you unman?’ Mindell, War, Technology, and Experience, 148.

97. Blair, ‘Upper Air Stunts Now Condemned.’ William Blair had made significant contributions to the early research in the radio transmission of weather data in the 1920s at the US Signal Corps. See DuBois, Multhauf, and Ziegler, The Invention and Development of the Radiosonde, 27–9 and 34, which gives Blair the credit for making ‘the first documented radiosonde flight’ in 1924.
100. Mindell, *Digital Apollo*. For a more recent debate, see Space, Policy, and Society Research Group, *The Future of Human Spaceflight*.
102. For the Sperry autopilot, see Hughes, *Elmer Sperry*; David Mindell, *Between Human and Machine*, chap. 3. For ‘blind flying,’ see Ocker and Crane, *Blind Flight*; Conway, *Blind Landings*. For a popular account of the changing operating conditions in the cockpit, see Patterson, ‘Who’s Flying This Ship?’

References


Patterson, W.A. ‘Who’s Flying This Ship?’ *The Saturday Evening Post*, 12 February 1938, 11, 52–5.


