Early Severe Thunderstorm Forecasting and Research by the United States Weather Bureau

JOSEPH G. GALWAY

Kansas City, Missouri

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ABSTRACT

In the early nineteenth century, fragmentary weather observing networks were established in portions of the United States, primarily to constitute a climatological history. The invention of the telegraph in 1833 and its availability to the public in 1845 eventually led to a nationwide observation network with the formation of a national weather service in 1870 within the Signal Service of the U.S. Army. While Lt. J. P. Finley of the Signal Service was developing techniques for the prediction of tornadoes, others, as Prof. Henry A. Hazen (also of the Signal Service) and the New England Meteorological Society, were studying the thunderstorm in hope of developing predictors for the forecasting of these events. The thunderstorm studies were carried over to the civilian U.S. Weather Bureau in 1891, but interest in thunderstorm and tornado research waned as a ban on the use of the word "tornado" in forecasts, inherited from the Signal Corps, was carried into the twentieth century. The growth of the aviation industry after World War I forced the bureau to accept the theories of the Norwegian school, as forecasts of thunderstorms and upper-air conditions (winds, ceilings, visibilities, etc.) were mandated by law. World War II brought greater changes with the development of the radiosonde and radar, and more emphasis was directed to the study of thunderstorms. Early in the war, the U.S. Weather Bureau was requested to develop warning networks in the vicinity of munitions plants to report the approach of thunderstorms in order to evacuate the plant workers to safety lest lightning struck. These networks spread to military installations, and eventually were organized for selected cities in tornado-prone areas of the central plains and the Missouri River valley. The Thunderstorm Project, conceived in 1943, began field operations in 1947 to obtain a detailed description of all phases of the thunderstorm, not necessarily to differentiate thunderstorm intensity. At the same time, Fawbush and Miller were in the process of developing criteria to make this differentiation in order to predict severe thunderstorms and tornadoes. In 1949, the Weather Bureau began to develop procedures to forecast severe local storms, which culminated in the formation of a crash research program called the Tornado Project. The success of experimental tornado forecasts by the project led to the establishment of the Severe Weather Unit (SWU) in May 1952 for the prediction of severe local storms nationwide. Later, it was renamed the Severe Local Storms Center (SELS), now a component of the National Severe Storms Forecast Center (NSSFC). Forecast development and research from 1950 to 1963 is presented with primary attention given to the development of techniques for forecasting severe local storms and the emergence of SELS as a viable forecast unit.

1. The role of the U.S. Signal Service

Thunderstorms attracted much attention both in this country and abroad during the latter part of the nineteenth century. While there was a reasonable grasp of the thunderstorm's components—that is, lightning, hail, heavy rains, wind gusts, and the tornado—little progress had been made in the area of thunderstorm prediction. In the United States, minor networks for organized meteorological observations were established by the Land Office in 1817, and in 1819 by the surgeon-general of the army. The telegraph, invented in 1833, was made available to the public in April 1845. This provided weather services worldwide with a rapid communications system of obtaining weather observations in real time. In 1847 the Smithsonian Institution inaugurated "a system of extended meteorological observations for solving the problems of American storms" (Abbe 1909). This voluntary network included 150 stations in the first year. Steady growth continued until there were 500 stations in the system by 1860. However, the outbreak of the Civil War resulted in a rapid reduction in the number of observers, and prewar size was never attained after the end of hostilities.

In December 1873, Joseph Henry, director of the Smithsonian, petitioned Gen. Albert J. Myer, chief signal officer of the U.S. Army and head of the Signal Service's recently established weather service, to assume the funding of the Smithsonian's voluntary weather observing network. The Department of Agriculture had been supporting the weather observation function, but the bank in which the Smithsonian had deposited the funds went into bankruptcy and the funds were lost. The Agriculture Department withdrawal of its support also meant a loss of the "franking" privilege, free post-

Corresponding author address: Joseph G. Galway, 5620 N. Adrian NW, Kansas City, MO 64151.

age (U.S. Army 1874). The Signal Service assumed responsibility for the network on 1 January 1874. Also, in 1873, the surgeon-general of the army dispensed with its meteorological work and transferred its records to the Signal Service. The observing network of the Signal Service provided the real-time weather observations used in the preparation of charts for the "indications officer" (forecaster). Little effort was made to compile a data bank for research purposes from the foregoing sources, however.

General Myer died in August 1880 and was succeeded by General William B. Hazen. Hazen, being more research oriented than Myer, hired four senior and three junior civilian scientists and in 1881 established a research unit called the study room. In 1882, Sgt. John P. Finley was transferred to the office of the chief signal officer and placed in charge of a project called tornado studies. The goal of the project was to collect and investigate tornado reports in order to develop procedures for the prediction of tornadoes. Finley proceeded to establish a network of "tornado reporters" east of the Rocky Mountains, which expanded from 120 reporters in 1883 to 2403 reporters by 1887. This network was composed of volunteers and was a separate group from the weather observations network of the Signal Corps. Finley began his tornado predictions in March 1884. He developed a chart of surface parameters he considered instrumental in the formation of tornadoes. This chart was called, interchangeably, the severe storms chart or tornado chart (Fig. 1). Finley's grasp of the tornado forecast problem was far more advanced than that of his contemporaries. Note in Fig. 1, for example, the intrusion of dry air, as indicated by isolines of the dewpoint depression, from Louisiana eastward into the surface moist tongue over eastern Alabama and western Georgia, an indicator of potentially severe activity used by severe storms forecasters today. The famous tornado outbreak of 19 February 1884 was in progress at map time.

While Finley was developing techniques for the prediction of tornadoes, a ban on the use of the word "tornado" in the indications (forecasts) released by the Signal Corps was issued by the chief signal officer in 1883 (U.S. Army 1885). The ban was lifted briefly in 1886. Signal Corps memorandum 100, 1886, stated "when conditions favorable for the occurrence of severe local storms or tornadoes are expected, a statement of this nature would be included as part of the general indication, giving the locations where such storms were expected to occur." Outside pressure on the chief signal officer is suspected as the memorandum also directed the indications officer to telegraph a special message to the directors of the Minnesota, Ohio, and Alabama state weather services, when located within the threatened areas (U.S. Army 1886a). However, the ban on forecasting tornadoes was reinstated early in 1887. For details on Finley's tornado project, the reader is directed to Galway (1985).

In January 1884, Prof. Henry Allen Hazen, one of the junior scientists assigned to the study room, petitioned General Hazen[1] to make a systematic study of thunderstorms during the upcoming summer. He argued that observers were spaced too far apart, and not uniformly distributed in previous networks. General Hazen approved the project and solicited the assistance of the postmaster general. Post offices 40 miles apart, from the Atlantic Ocean to 102°W and from 34°N to the Canadian border, were enlisted to take thunderstorm observations for the summer of 1884, to supplement the observations of the Signal Corps stations. In his instructions to the observers, Professor Hazen included a delineatory wind-speed scale of calm, light, moderate, brisk, high, very high, and hurricane or tornado.

An earlier list of studies and problems for investigation by Signal Corps personnel included the frequency of high winds, that is, 25 to 40 mph (22 kt to 35 kt), and storm winds, that is, 40 mph and over (35 kt and over) (U.S. Army 1881). The foregoing wind categorization had a long life, although their accompanying adjectives would change. The 1935 edition of the *Manual of Airway Observations,* Circular N, defined a moderate thunderstorm as one with winds reaching 40 mph (35 kt), and a severe thunderstorm as one with winds in excess of 40 mph (35 kt) (U.S. Weather Bureau 1958).

Hazen (1885) presented preliminary results for the thunderstorm activity during May 1884. These included that thunderstorms move faster than the parent surface low center, and that thunderstorm activity decreased at night and reformed again during the daylight hours. In an expanded paper on the thunderstorms of 1884 (U.S. Army 1886b), Hazen associated thunderstorm activity with temperature, pressure, relative humidity, the phases of the moon, and solar rotation about its axis (25.38 days). Results were mixed. Some association was noted between periods of temperature above the mean and thunderstorm activity. Also, some association between pressure below the mean and thunderstorms was found. No association with thunderstorms was observed with relative humidity, for stages of the moon, and solar rotation. Hazen wrote, "The results need further study."

The New England Meteorological Society, founded in 1883, initiated a study of New England thunderstorms in the summer of 1885. Funds for the study were provided by the Signal Corps and the National Academy of Arts and Sciences. A call for volunteer observers brought a response from nearly 500 individuals in various parts of New England offering to assist in the study. About 300 of these maintained their in-

[1] Previous authors, including this one, indicated no relationship between the two Hazens. Recent findings reveal that the Hazens were second cousins once removed, however.

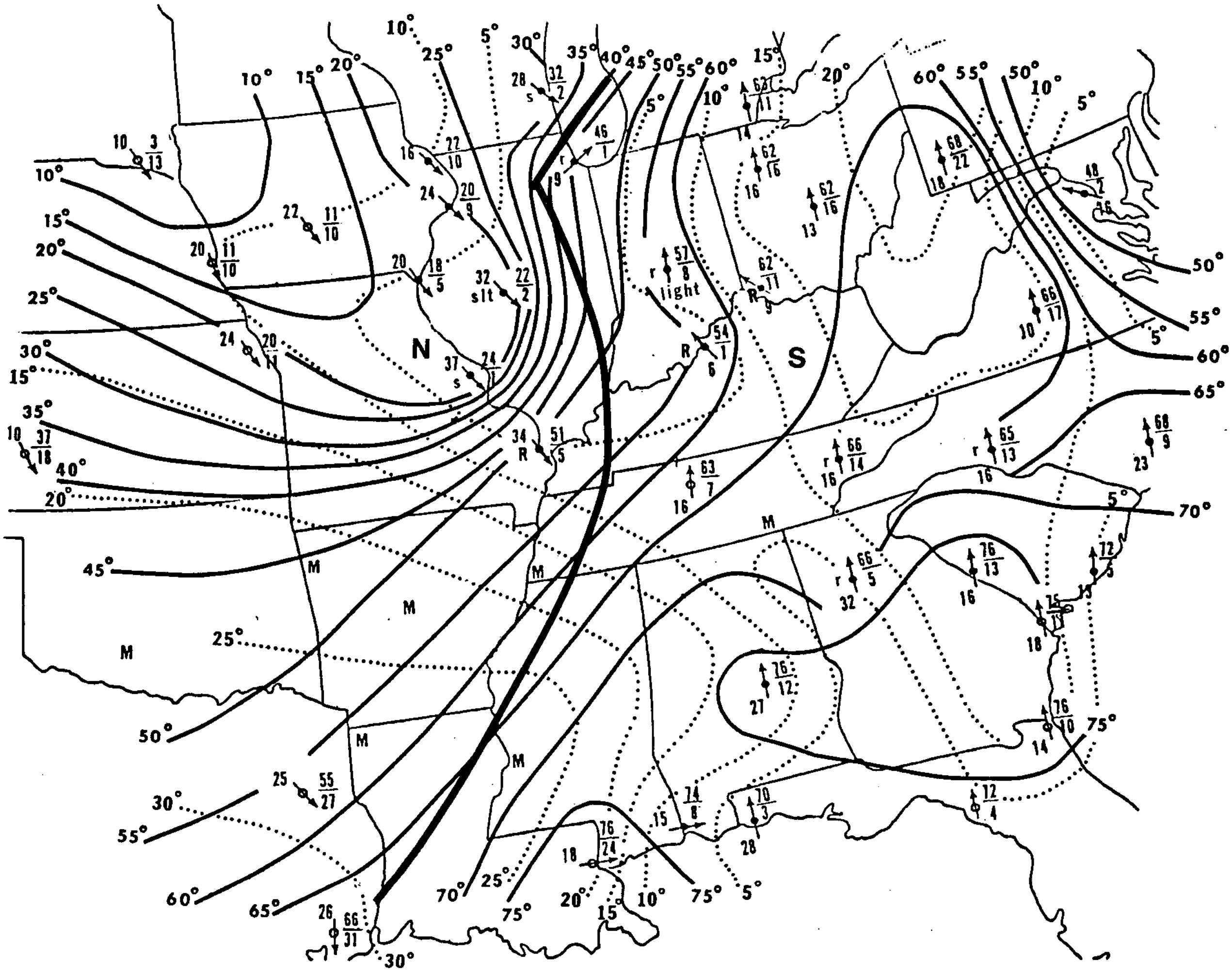

FIG. 1. Recreation of Finley's "tornado chart" from data for 2100 UTC 19 February 1884. Station model consists of temperature (top) and dewpoint depression (bottom) to right of station; wind direction and speed; and current weather. Temperature and dewpoint depression drawn for each 5°F. Precipitation intensity (light or heavy) indicated by small r and capital R for rain, s and S for snow, slt and SLT for sleet, etc. Open station circle—clear or fair; solid station circle—overcast. Heavy line separates regions of northerly (N) and southerly (S) winds (U.S. Army 1886a).

terest through the summer. Davis (1887) presented a general account of the thunderstorms during the period of study. His summary included an hourly distribution of thunderstorms and concluded both that thunderstorms are controlled by the larger cyclonic circulation and that the direction of motion of the thunderstorms is nearly parallel with the higher (upper-air) winds. In 75% of the cases studied, the thunderstorms moved east or southeast, indicating a westerly or northwesterly flow aloft (Fig. 2). This is consistent to what is observed today for New England (Galway 1958). The New England Meteorological Society continued its thunderstorm research during the summers of 1886 and 1887 but lost most of its support from the Signal Corps.

In the mid-1880s, a controversy between groups that favored civilian control of the weather service and those that sponsored military control became a political issue. A congressional group, the Allison Commission, conducted an investigation of the corps from 1884 into 1886. The commission's report of June 1886 recommended not only civilian control of the weather service but also that the training center at Ft. Myer, Virginia, be closed. This meant the demise of the study room, but General Hazen was able to retain the civilian scientists. The tornado project of Finley and Professor Hazen's thunderstorm investigations were abolished. Also, the publication of *Professional Papers of the Signal Service* and *Signal Service Notes* was discontinued as they were not required for the current work of the corps. The *Monthly Weather Review* was spared and its publication continued (U.S. Army 1886c). However, reports of tornadoes and thunderstorms continued to be received and filed by the Meteorological Records Division. Finley was placed in charge of that di-

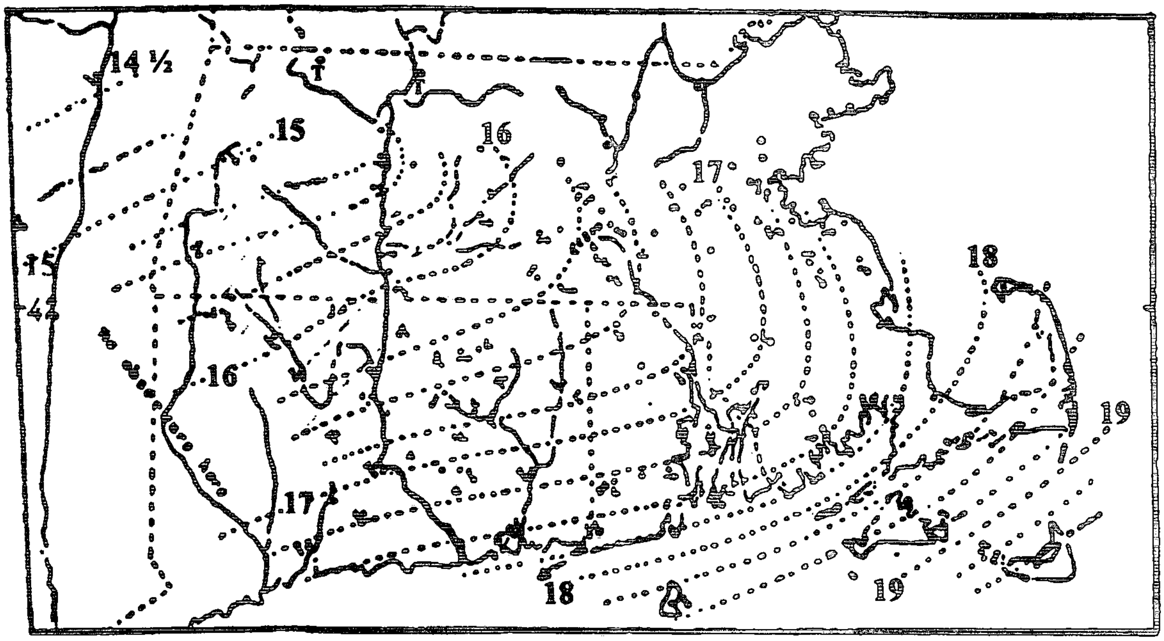

FIG. 2. Movement of squall line across southern New England on 21 July 1885. Dotted lines indicate position in 15-min increments. Times are local standard (after Davis 1887).

vision with Professor Hazen as his assistant. This was ironic, as the views on tornadoes of these two researchers were diametrically opposed (Galway 1985).

General Adolphus W. Greely became the chief signal officer upon the death of General Hazen in January 1887. In his annual report for 1887 (U.S. Army 1887), Greely stated his position on tornadoes and thunderstorms. He said that

> although [he was] pressured to continue the predictions of tornadoes, [he] believe[d] that neither the present condition of the science of meteorology nor the practical needs of the country would justify such forecasts . . . and that more harm would be done by the prediction of a tornado than from the tornado itself.

He approved of an occasional prediction that conditions are favorable for severe local storms. On the question of thunderstorms, he wrote, "the investigations of the New England Meteorological Society had been more full and complete than if performed by the Signal Corps." The decisions by Greely brought an end to formal research on severe local storms by the weather service of the Signal Corps.

2. A civilian weather service

On 1 October 1890, four years after the Allison Commission filed its report urging that the weather service be removed from army control, Congress passed a bill transferring the weather service to the Department of Agriculture, effective 1 July 1891. The civilian scientists of the Signal Corps were restored to their original status as research meteorologists under the newly created Weather Bureau. One of the first projects approved by Chief of Bureau Mark W. Harrington was the investigation of thunderstorms during the summer of 1892 to ascertain the feasibility of making thunderstorm forecasts, and to obtain better knowledge of their characteristics. The area selected for study embraced the region from the upper Mississippi valley eastward to the Atlantic coast, including New England (Conger 1893). The area was similar to that used by Professor Hazen in his investigation of 1884 but did not include the plains states.

There were no guidelines or rules in effect for forecasting thunderstorms from the daily weather charts; however, it had been noted that during the summer months (June–August) 90% of the thunderstorms occurred in a belt covered by the isobar of 30.00 inches or less and at or near the 70°F isotherm on the 1300 UTC surface weather chart. The results of the Weather Bureau investigation confirmed earlier studies by the New England Meteorological Society that there were two classes of thunderstorms. One class moved in a regular progression from west to east associated with a surface cyclonic system. Storms in the second class, referred to as "heat thunderstorms," occurred over a large area without a definite path of progression, and were not as intense as those in the progressive class. The report also noted that "the presence of a low (pressure) area to the west, moving behind a high (pressure) area, should be watched with great care as the thunderstorm conditions are very liable to develop during the afternoon or evening; the sharp curvature of the isobars, especially where it touches or crosses similar sharp curves of temperature, has been found to be of value in forecasting (thunderstorms)." The sharp curvature of the surface isobars was called a V-shaped trough with the point of the V pointing toward the equator. The term was first used by European meteorologists late in the nineteenth century and by meteorologists in the United States early in the twentieth century.

The forecasts made from the daily weather maps during the span of the investigation were fairly successful. An effort was made to forecast all thunderstorms, whether light or heavy, and not to forecast only the severe thunderstorms. Verification for Ohio, Michigan, and the New England states showed a forecast accuracy of 86% for June, 83% for July, and 69% for August. The drop in August was due to the small number of storms in Ohio. The thunderstorm investigation was continued for the summer of 1893 over an expanded area (Clayton 1893), but no formal study has been located by this author.

In July 1895, Harrington was dismissed as chief of the Weather Bureau by President Grover Cleveland. This culminated a lengthy feud between Harrington and J. Sterling Morton, the secretary of agriculture. Willis L. Moore, the official in charge at Chicago, Illinois, was appointed as chief five days after Harrington's departure. Moore continued the research in aerology, climatology, and meteorological instruments established by Harrington, and added investigations into evaporation, solar radiation, clouds, and wireless telegraphy. Moore ordered the reevaluation of severe storm reports for the period 1889–1896 (Galway 1989), criticizing the method used by the Signal Service in the collecting of tornado reports and belittling the skill and integrity of the tornado reporters (Moore 1896). He favored the method of Dr. Gustavus Hinrichs of the University of Iowa and head of the Iowa State Weather Service, who recorded the number of tornado days rather than the individual tornadoes. Moore did not propose any improved method for the collection of tornado reports. This resulted in an era of almost complete absence of research by the U.S. Weather Bureau on severe local storms.

From 1897 until 1916 there was no central collection point for severe local storm reports within the U.S. Weather Bureau. Reports of severe storms occasionally appeared in the *Monthly Weather Summary* of the state section directors or the *Monthly Weather Review*. These were the more intense storms, however, usually associated with tornado outbreaks that resulted in large death tolls and widespread damage. National meetings of Weather Bureau officials were held at Omaha, Nebraska, in 1898; at Milwaukee, Wisconsin, in 1901; and at Peoria, Illinois, in 1904. A total of 131 papers on all phases of the weather service with the exception of severe local storms were presented at those meetings. A paper at the Milwaukee meeting reporting on an instrument that recorded lightning flashes was the only paper that was related to convection in the three meetings.

A few papers on tornado and thunderstorm dynamics or the forecasting of these events by European meteorologists appeared in the *Monthly Weather Review*. In one, Varney (1926) wrote, "It is remarkable that in the United States, more afflicted with tornadoes than any other area of equal size on the globe, the literature of tornadoes since Ferrel is confined almost exclusively to compilations of statistics on distribution, frequencies of occurrence, descriptions of resulting damage, and so on." This continued for the next decade. Weather Bureau meteorologists were also slow to accept the theories of the Norwegian school. Frontal analysis was accepted by the aviation forecasters in 1936. It was not until 1938 that airmass analysis was adopted by the bureau, and by the end of the 1930s fronts finally appeared on the *Daily Weather Map* released to the public (Williams 1990).

A deterrent to research on severe local storms in the first four decades of the twentieth century was a ban on the use of the word "tornado" in forecasts. This ban was inherited by the U.S. Weather Bureau when the weather service was transferred from the Signal Corps to the Department of Agriculture. The ban appeared periodically in station regulations until 1938. There were those who continued to search for the basic cause of severe local storms, however. As noted by Schaefer (1986), Jakl (1920) suggested that cold air aloft over a warmer air mass was the destabilization mechanism in the formation of severe local storms. The evidence presented by Humphreys (1926), Varney (1926), Wexler (1935), and Lloyd (1942) led to the belief that "tornadoes appear to occur only in connection with upper cold fronts." Schaefer also pointed out that Newton (1950) "demonstrated that prefrontal squall lines are not necessarily associated with a cold front aloft, but result from the convergence that occurs with subsiding high velocity air from aloft meeting relatively slower boundary layer air."

Other investigators pursued different courses. Weightman (1933) found that tornadoes occurred under a great variety of meteorological conditions: for example, with warm-front thunderstorms, hurricanes, ill-defined discontinuities, the centers of lows, and the passage of the surface cold fronts. The Meteorological Physics Division of the Weather Bureau in the *U.S. Meteorological Yearbook* of 1936 (U.S. Weather Bureau 1938) discussed two tornado outbreaks in April 1936. One contained storms that formed along the surface cold front, while with the other the tornadoes occurred 50 to 100 mi ahead of the cold front. Lemons (1938), in a study of Nebraska tornadoes over a 22-year period, found that 95% of the tornadoes formed with the surface cold front, 1% with the surface warm front, 3% indicated similar places of inception, and 1% gave no clues as to the places of origin. Major changes in the operations and research of the weather service soon would occur, however, as hostilities that began in September 1939 resulted in World War II.

4. The Weather Bureau and World War II

Under authority of Reorganization Plan No. IV, which was submitted to the Congress on 11 April 1940, the Weather Bureau was transferred from the Department of Agriculture to the Department of Commerce on 30 June 1940. The development of the aviation industry was given as the primary reason for the transfer (U.S. Department of Commerce 1948). In July 1940, representatives of the army, navy, and Weather Bureau met to discuss proposals for research in improvement of weather forecasting and plans for training weather forecasters. The committee was designated as the Defense Meteorological Committee. After the United States' entrance into the conflict, the committee became the Joint Meteorological Committee. Abundant funds were made available for research and operations, which resulted in an increase in radiosonde observations, an extension of weather services in Alaska, and the establishment of improved and increased weather reporting over the Atlantic and Pacific oceans. Also, there was a large expansion of domestic services in the area of severe local storms.

An initial action of the committee was to inaugurate specific forecasting programs for military establishments, munitions plants, and transportation. By 1940, many munitions plants were producing explosives. They required information about the weather, especially thunderstorms. The U.S. Weather Bureau organized a severe storm warning service to issue advisories to plant officials of impending thunderstorms. These advisories enabled officials to evacuate personnel to minimize casualties in case a lightning strike set off high-explosive materials. The severe storm warning plan consisted of recruited observers stationed at several points in all directions from the munitions plant (normally in about a 35-mi radius of the plant). Reports of approaching thunderstorms were telephoned to a central Weather Bureau station or directly to the plant for interpretation and, ultimately, for use in evacuation of workers. The service provided proved so effective that by December 1942, 100 networks had been established around plants engaged in the manufacture or storage of ammunition and military supplies (U.S. Department of Commerce 1948).

When the United States entered World War II in December 1941, strict censorship was imposed on weather information. In the interest of the overall war effort, however, the military authorities approved a clearance system permitting the general broadcast of warnings of severe weather conditions, such as cold waves, hurricanes, severe local storms, and heavy snows in 1942. Forecasts, in generalized terms over 26-h periods, were also permitted (U.S. Department of Commerce 1942). This prompted a change in the reporting procedures of the ordnance plant observers. In June 1942, the Kansas City, Missouri, Regional Office of the Weather Bureau issued a confidential letter to ordnance weather observers asking that they report hail, strong winds, and tornadoes in addition to thunderstorms. But the cloak of confidentiality was constructed like a sieve. It was not long before the public and the press were demanding warnings of these events. The central portion of the country had endured a large number of tornadoes in 1942 and the concern for being forewarned ran high. The result was the formation of experimental tornado warning systems in the spring of 1943 in the vicinities of Wichita, Kansas; Kansas City, Missouri; and St. Louis, Missouri.

During 1943, requests for the formation of storm-warning networks around air fields, training camps, and other military posts from all branches of the military were made of the Weather Bureau. The bureau was aided in this effort by the Office of Civil Defense and the military forces. By June 1945, nearly 200 networks were in operation (Fig. 3), in addition to previously established networks in the vicinity of the munitions plants. The Weather Bureau published a pamphlet in June 1944 on the reporting of severe local storms for network observers. The types of storms to be reported included tornadoes, thunderstorms (including hailstorms and lightning storms), and high winds. The pamphlet also contained information on recognizing tornadoes and thunderstorms, protection against tornadoes, and instructions on what to report (location, time, movement, etc.). The storm warning brochure was the first publication by the bureau, as best as can be determined, to define a severe local storm. The publication provided some insight as to the tenor of thought on severe local storms in that era. It pointed out that (U.S. Weather Bureau 1944)

> [the forecaster] can make advanced weather forecasts of weather conditions favorable for severe storms over a general area, but these predictions cannot give the exact time a severe storm will be at a definite point. Specific warnings can be made only after a storm is in progress and a report has been received on the type and location of the storm. The forecaster can then determine the direction of the path of the storm to a very accurate degree for the next few hours and warn people who may be affected.

From this, it is obvious that restraint was expected of the forecaster with regard to severe local storm *forecasts,* but that *warnings* were permissible once the storm had formed. This was in concert with a Weather Bureau circular letter issued 1 June 1943, which stated that alerts (forecasts) were more trouble than they were worth. It was felt that such releases would first cause public alarm and panic, followed by indifference in the future if tornadoes did not occur during the alert (Whitnah 1961).

The War Advisory Council on Meteorology, staffed by Weather Bureau personnel, was established by the

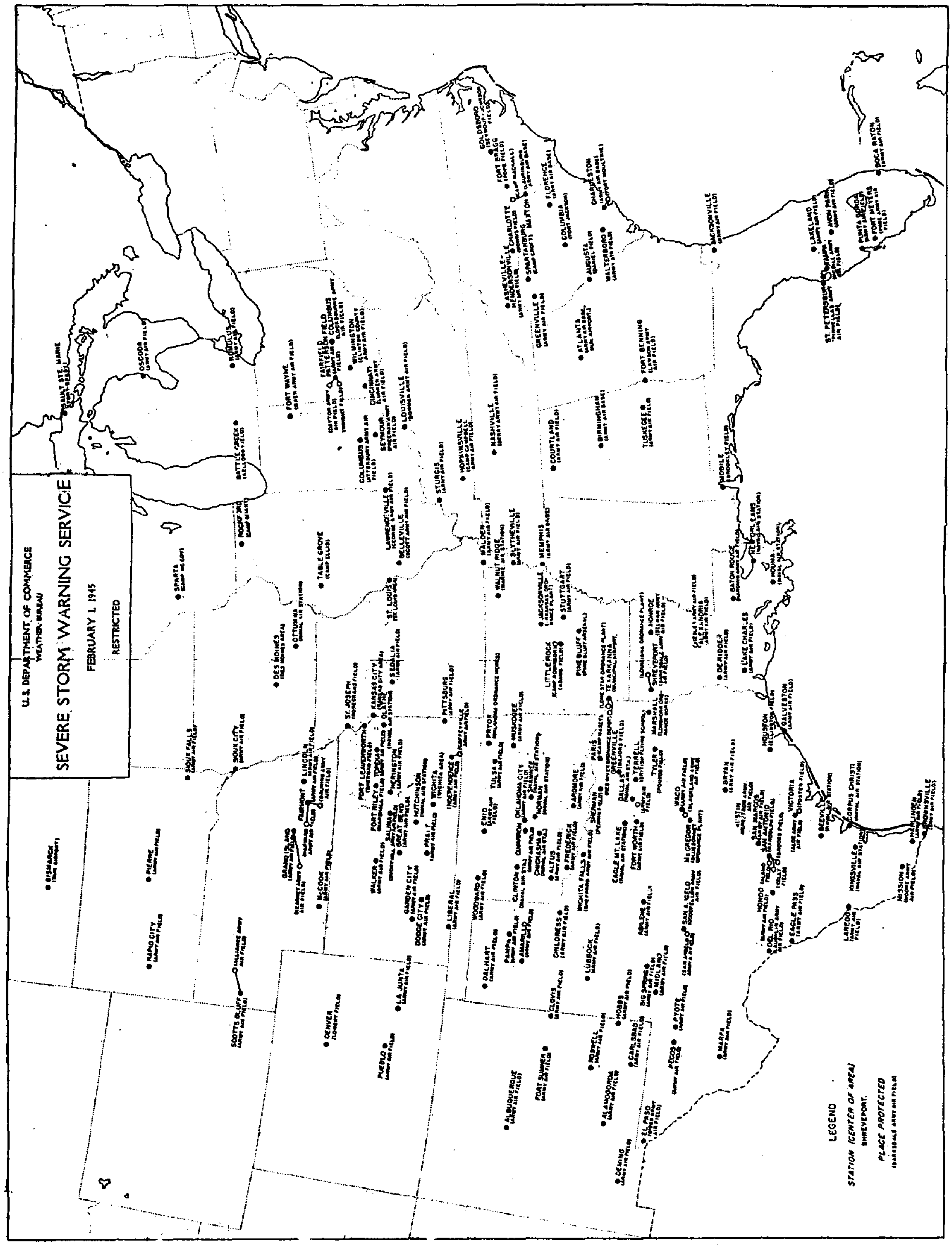

FIG. 3. Networks of the Severe Storm Warning Service in February 1945 (U.S. Weather Bureau 1945).

chief of the Weather Bureau in October 1942. The overall objective of the Council was to provide assistance to the armed forces on meteorological and related problems, as assigned by either the Joint Meteorological Committee or the chief of bureau. It was an on-call research unit until it was disbanded in November 1945. The majority of the council's work was based on climatological studies and used for long-range planning of military objectives. Generally, studies were intended to improve and extend the range of forecasts, and to compile special summaries of ceiling and visibility data for "flying weather" statistics; however, the council received an urgent request for the latest information on the formation of tornadoes early in 1943. This was definitely in the area of domestic services and, no doubt, was prompted by the large loss of life by tornadoes in 1942. The result was a two-paper publication by Showalter and Fulks (1943).

Showalter's paper presented a theory of tornado formation. It discussed synoptic conditions associated with tornadoes, a summary of upper-air data associated with recent tornadoes, and a summary of selected tornadoes. His list of prominent surface conditions included pronounced cyclonic horizontal wind shear in the region of tornado formation, convergence, or a frontal zone, potentially unstable air (indicated by thunderstorm activity), pronounced latitudinal wind shear, and either local wave development or widespread cyclogenesis. Also, he pointed out that the thermal factor is as important in the formation of tornadoes as is the lifting or horizontal convergence.

Fulks' paper analyzed the synoptic conditions associated with the Hackleburg, Alabama, tornado of 12 April 1943. He wrote, "The tornado occurred along and near the leading edge of a relatively dry and unstable airmass nosing in aloft over lower maritime tropical air and the tornado was associated with the development of a secondary low pressure some 50 miles to the north." The publications of Showalter and Fulks and the works of Lemons (1939), Lloyd (1942), and Varney (1926) would be expanded later by Fawbush and Miller of the Air Weather Service (AWS). They postulated a requirement for the simultaneous occurrence of six criteria in areas where tornadoes could be expected to occur (Fawbush et al. 1951).

Prior to Showalter and Fulks, Brancato (1942) made a hydrometeorological investigation of flood conditions caused by thunderstorm rainfall. In his discussion of energy transmission within the thunderstorm, he "used data from an upper-air sounding to develop a formula to calculate wind velocity which would result from evaporational cooling of the air." The speed of the thunderstorm relative to the surface of the earth was added and the total approximated the surface wind speed. In a different area, Jakl (1944) presented a theoretical discussion of wind pressure associated with circular depressions. He also presented equations to derive tornado pressures.

In 1943, an airline coalition proposed in a letter to the Civil Aeronautics Board that a detailed description of all the phases of the thunderstorm was needed. Early in 1944 a committee comprising representatives from the government, airlines, and universities met for preliminary planning. A year later, the final decision to launch a major project was made. The Weather Bureau assumed responsibility for organizing the project. Funds were appropriated by Congress in July 1945 for the program, designated as the Thunderstorm Project. Field operations were held in the Orlando, Florida, area during the summer of 1947 and in the vicinity of Wilmington, Ohio, in the summer of 1948 (Byers and Braham 1949). The data and information collected produced numerous papers and studies. These included reports on turbulence, wind shear, squall lines, and the like. Interest spread to the universities and meteorological departments of the airlines. These sources added to the wealth of information on the thunderstorm in the postwar years of the 1940s and early 1950s. While it was not an objective of the project to differentiate thunderstorm intensity, that is, severe versus nonsevere, during the same time span two U.S. Air Force meteorologists were in the process of developing criteria to make this differentiation in order to predict severe thunderstorms and tornadoes.

5. The tornado project

On 20 March 1948, a tornado struck Tinker Air Force Base (AFB) near Oklahoma City, Oklahoma, destroying 32 military aircraft and causing severe damage to a number of structures on the base. The AWS domestic wing was based at Tinker, and its commander summoned two of his top forecasters, Maj. Ernest J. Fawbush and Capt. Robert C. Miller, and asked if better advanced warning of severe weather could be provided. They had already been working on an empirical technique for the prediction of severe thunderstorms and tornadoes, and five days later were able to provide some warning for another tornado that hit the base, destroying what the first one had missed (Bates and Fuller 1986).

Fawbush and Miller continued to work on their technique and the experimental tornado forecasts issued for central Oklahoma were very successful (Air Weather Service 1952). Although the forecasts were distributed only to air force weather offices, their existence and success became known to the public and especially to the local media, which lauded the efforts of the air force while criticizing the Weather Bureau for its inaction to forecast this weather event. In January 1950, Fawbush and Miller presented a paper on their tornado forecasting technique at the 30th Annual Meeting of the American Meteorological Society, held in St. Louis, Missouri. Damaging tornadoes occurred near St. Louis the evening prior to the meeting and were very much in the news. This enhanced interest in the Fawbush and Miller paper, giving it national publicity (Beebe 1984).

Their early successes in tornado forecasting prompted the Weather Bureau to invite Fawbush and Miller to visit and discuss their forecasting procedures. They made several trips to the district forecast office in Kansas City, Missouri, during late 1949 and early 1950. This was complemented by research meteorologists from the central office in Washington, D.C., traveling to Tinker AFB to consult with Fawbush and Miller. While a scattered few within the Weather Bureau praised the Fawbush/Miller forecast technique, the consensus of most bureau officials and senior forecasters was that there was not enough merit in the forecast procedures to justify any change in Weather Bureau policy; that is, the nonrelease of tornado forecasts to the public (Beebe 1984).

Nonetheless, Chief of Bureau F. W. Reichelderfer, who by Public Law 657 (U.S. Congress 1948) had the authority and funds to study the causes and characteristics of thunderstorms and other severe atmospheric disturbances (including tornadoes), was cautious enough not to discredit the Fawbush/Miller technique without a thorough investigation of its validity. Thus, late in 1949, a call went out from the central office for data to be used in making studies of the nature of tornadoes and the processes that led to their occurrence. Field stations that had had a tornado pass close by in the past were asked to forward wind and pressure data plus other pertinent information to either the Chicago, Illinois, forecast office or to Washington (U.S. Weather Bureau 1949). This request started a crash program to investigate and test the Fawbush/Miller technique, to test existing premises for tornado formation, and to cull from the field stations local studies on thunderstorms and tornadoes.

One of Reichelderfer's first moves was to assign V. E. Jakl to review the Fawbush/Miller forecast technique. Jakl, a consultant to the chief on problems related to forecasting and to field organization, had long service with the bureau that ranged from observer to regional director. He was knowledgeable in dynamics and thermodynamics, and had previously presented theoretical discussions of tornado formation and tornado dynamics (Jakl 1944, 1949). Jakl met with Fawbush and Miller in February 1950 at Kansas City and was impressed by both their seriousness about tornado forecasting and the accomplishments they had thus far attained. He echoed the consensus opinion, however, that while the techniques employed by the Tinker Field weather staff contained all the variables inherent to thunderstorm forecasting, the technique allowed tornado forecasting only to the extent of saying that tornadoes are likely under given synoptic conditions. They did not allow for sharply defined or limited areas (Jakl 1950). The prime objection to the Fawbush/Miller technique by bureau officials was that the technique failed to pinpoint tornado occurrence. This is still intrinsic to forecast techniques today.

Dr. Morris Tepper of the bureau's Scientific Services Division postulated that "a squall line might be considered as a disturbance generated by accelerations along the cold front which travels along the warm sector inversion as a gravitational wave." He suggested that any series of meteorological events similar to this mechanism be called a "pressure jump line." Also, he proposed that the intersection of two pressure jump lines was a preferred zone for tornado formation (Tepper 1950).

A small pilot project was established in the vicinity of Washington, D.C., to get into the practical side of the "pressure jump" investigations. Sixteen existing Weather Bureau, military, or cooperative weather reporting stations with automatic equipment to record pressure, temperature, humidity, precipitation, and wind within a 50-mile radius of Washington were selected. The project was conducted from January to June 1950, and the results indicated that a full-scale program was justified.

This expanded program to investigate pressure jumps, called the Tornado Project, was conducted mostly in Kansas and Oklahoma. The observational network (Fig. 4) contained 134 stations, including six regular weather-reporting stations and 34 cooperative stations. A high-speed microbarograph was installed at each of the 134 stations. In addition to the microbarograph, each of the 34 cooperative stations received a recording raingage and a 12-h hygrothermograph. The Tornado Project also received some 300 special radiosonde or rawinsonde soundings from sites in and near the project area. Radar coverage was provided to the project by the Weather Bureau offices at Wichita, Kansas, and Norfolk, Nebraska, and by the AWS at Offutt (Omaha, Nebraska), Sherman (Ft. Leavenworth, Kansas), and Vance (Enid, Oklahoma) air force bases. These sites had radar cameras that were to be operated at the discretion of the individual operators.

In 1951, the Tornado Project found that there was "some evidence of compatibility between the observational data and the pressure jump line theory" (Tepper 1954). Also, while describing the project's first season, Tepper (1951) noted,

> Unfortunately for meteorological knowledge, the setting up of the Tornado Project system seems to have provided the people of Kansas with the best tornado insurance they ever had. For at the present writing (June) there have been no tornadoes in the "arc" area during 1951.

[The arc area was the area in Kansas lying near a concave line from near Kansas City, Missouri, to Anthony, Kansas, on the Oklahoma border (see Fig. 4).]

The Tornado Project continued for a second season, February through August 1952, in the Kansas–Oklahoma area, but was renamed the Tornado and Squall

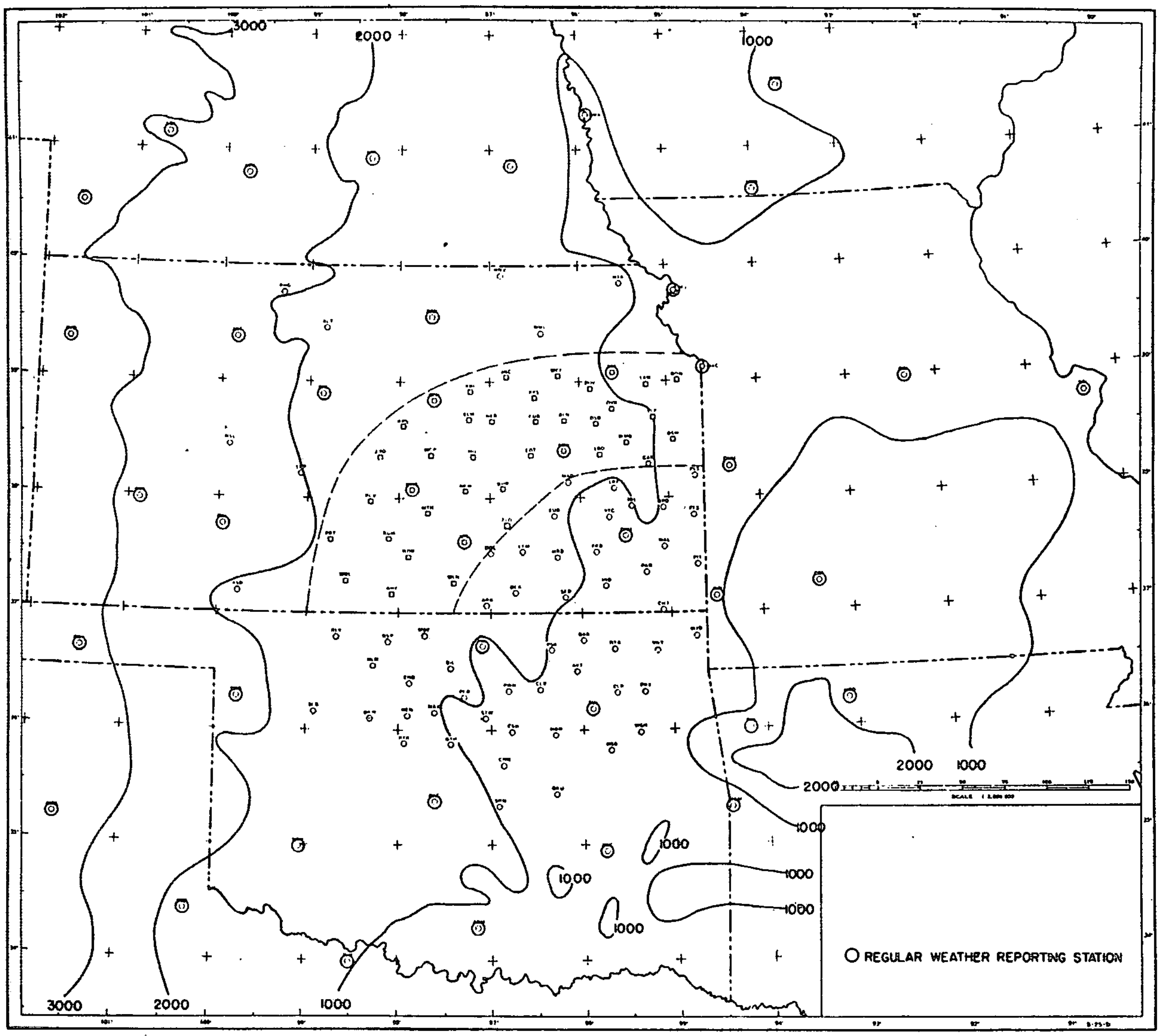

FIG. 4. 1951 Tornado and Severe Storm Observational Network. Regular weather-reporting stations are encircled. "Arc" stations are enclosed in two dashed parallel lines. Contours of elevations are in feet (after Tepper 1954).

Line Project. The AWS provided additional rawinsonde stations at Fort Sill, Enid, and Gage in Oklahoma and at Amarillo, Lubbock, and Waco in Texas from February through 15 June. These were mobile stations, which then were moved northward into Kansas and eastern Colorado until 31 August. There was no change to the surface observational network, nor to the radar coverage from the 1951 season.

A total of 143 tornadoes were reported over the network in 1952. Williams (1953) noted that 78% of the pressure wave (jump) lines were accompanied by thunderstorm activity, and tornadoes occurred with 27% of the lines. While Williams stated that the 27% figure was significant, he did not mention the relationship of tornado occurrence to intersecting pressure jump lines. Tepper (1954) concluded that the majority of tornadoes developed through some mechanism other than intersecting pressure jump lines.

The pressure jump line project began its third season, 1953, with still another new name, the Severe Local Storms Research Unit, and the observational network was expanded to cover all or parts of 10 states (Fig. 5). The 1953 network comprised 67 regular reporting stations [Weather Bureau, air force, and Civil Aeronautics Administration (CAA)], and 128 cooperative or other stations. Since it was recognized that the tornado and the thunderstorm were products of mesoscale systems, this 195-station network provided mesoscale observations. Mesoanalysis was the basic tool of the unit. Some of the observations from the 1953 season

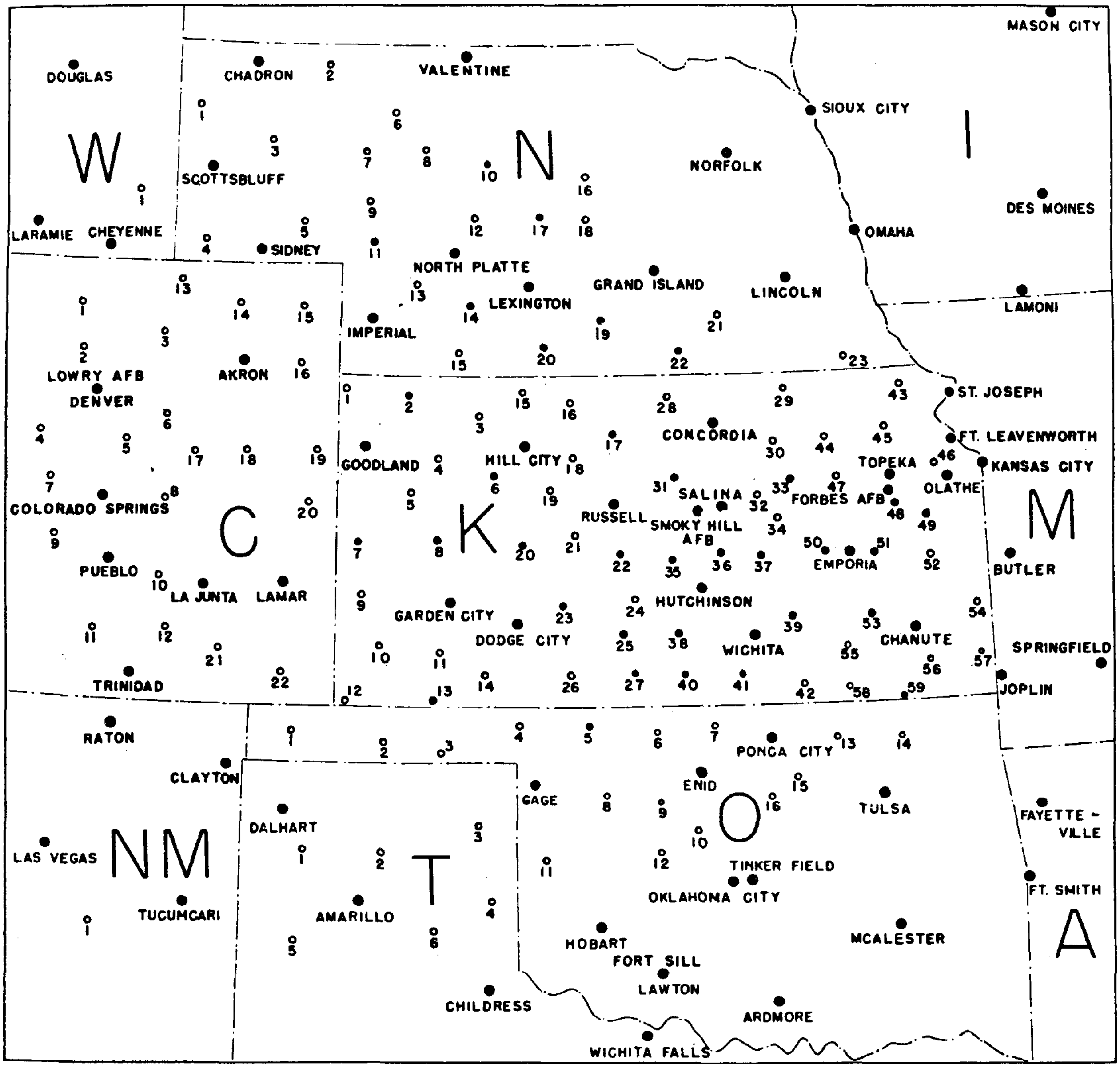

FIG. 5. 1953 Tornado and Severe Storm Observational Network. Large filled-in circle indicates regular weather-reporting station; small filled-in circle, cooperative station with microbarograph and hygrothermograph; open circle, cooperative station with microbarograph only (after Fujita et al. 1956).

were published by Fujita et al. (1956). They included a thoroughly analyzed severe storm system that passed across the observational network. In this case, the tornadoes were associated with a pressure couplet (pressure fall and rise combinations on the surface chart) rather than a pressure jump line. This was in agreement with the earlier finding by Donn et al. (1954) that squall lines may occur with or without associated pressure jumps. While the existence of the pressure jump line was not in question, its relevance as a causative factor for severe local storms was.

6. Preliminary forecast studies

As an adjunct to the Tornado Project, knowledgeable field personnel were assigned to temporary duty at the Weather Bureau's central office to develop techniques for forecasting severe local storms. In addition, all operational people were encouraged to submit local studies, preferably proposing forecast parameters, on severe local storms. This action was initiated during 1950, and when the first public releases of tornado and severe thunderstorm forecasts from the Weather Bureau–Air

Check List of Criteria
for Severe Local Storm and Tornado Forecasting
WBAS Kansas City - 1953

YES NO

Vertical Structure

1. "Typical" airmass structure - moisy surface layer at least 3000 but less than 8000 feet thick with mean mixing ratio 8g/kg or more and R.H. 65% or more, overrun by deep dry layer with R.H. dropping off abrubtly to 50% or less above moisture inversion. ___ ___

2. Conditional and convective instability above moisture inversion. ___ ___

3. Showalter Stability Index -5°C or lower. ___ ___

4. Level of Free Convection (LFC) 650 mb or greater. ___ ___

5. Strong positive area on sounding. ___ ___

Upper Air Conditions

6. Low level (5,000') southerly axis of maximum winds 35 knots or over, with 850 mb moist tongue. ___ ___

7. 700 mb dry tongue (R.H. less than 50%). ___ ___

8. Upper level (16,000') westerly axis of maximum winds 35 knots or over. ___ ___

9. Warm air advection below the LFC. ___ ___

10. Cold air advection above above LFC. ___ ___

Surface Conditions

11. Dew point ridge from the south, 55°F or greater, with steep gradient on the western side. ___ ___

12. Strong convergence - cyclonic wind shear. ___ ___

13. Lifting mechanism - front, instability line, semi-micro High or Pressure Jump line. ___ ___

REMARKS:

FORECASTER________________ TIME________ DATE____________ 195__

FIG. 6. Kansas City check list for forecasting severe local storms and tornadoes (after Foster 1953b).

Force–Navy (WBAN) Analysis Center in Washington began in March 1952, the efforts of this phase of the project became evident.

One of the first items developed was "potential instability" (PI) data. PI data were obtained from an analysis of the individual upper-air soundings, which included the level of free convection (LFC, mb), the mean mixing ratio (g kg^{-1}) in the layer from the surface to the base of the dry-bulb temperature inversion, and the height of the dry-bulb inversion (100 ft^2). If there was no LFC, or the LFC was above the 400-mb level, a code figure, 39, was reported. The data were used by the personnel at the Analysis Center while making severe weather forecasts during March, April, and early May 1952, and were made available via teletypewriter circuits to the field forecast centers in April 1952.

The PI data were transmitted twice daily as soon as possible after receipt of the 0300 UTC and 1500 UTC upper-air data. The forecast centers plotted the data and analyzed fields of the LFC and depth of the moist layer. Other conditions being favorable, it was found that tornadoes were most likely to occur within the area where the pressure at the LFC was 650 mb or higher, with the first outbreak of storms occurring along the windward edge of the area (Fawbush et al. 1951). Lloyd (1942) found that the critical depth of the low-level moist layer ranged from 3000 to 8000 ft, with about 5500 ft being most favorable for tornado occurrence. Transmission of PI data was discontinued in September 1952, as the permanent Severe Weather Unit (SWU) assumed the preparation of special charts and the release of forecasts for severe local storms.

Worksheets of parameters favorable for the development of severe local storms were constructed by some forecast offices, among them Chicago, Kansas City, and Great Falls, Montana (Fig. 6). These basically were consistent with the Fawbush/Miller criteria, although parameters such as the intensity of the 12-h surface pressure falls and negative Showalter Stability Indices (SSI) (Showalter 1953) were included. In general, the worksheets were not designed to be a forecast rote but to stress parameters that, although not sufficient, were recognized to be necessary in the formation of tornadoes and severe thunderstorms. A comprehensive list of suggested criteria for tornado forecasting that included vertical structure (stability, LFC, etc.), surface features, upper-air features, climatological aids, and objective aids was assembled by Shuman and Carstensen (1953) of the Scientific Services Division (Fig. 7).

Stability indices to augment the SSI began to appear in 1952. Means (1952) proposed that the surface parcel rather than the 850-mb parcel be lifted to 500 mb and its temperature subtracted from the observed 500-mb temperature. He argued that the density and frequency of surface observations made this index especially applicable since changes in the 500-mb temperature were for the most part fairly conservative during a given 12-h period. Younkin (1953) developed a method of computing the available energy above the LFC, which involved a determination of the LFC and 500-mb lifted parcel temperature from the sounding. Essentially, the mean lapse rate from the LFC to 500 mb was obtained by the equal area method and the temperature difference at 500 mb between the lifted parcel and the mean lapse rate was computed. Younkin constructed a nomogram of LFC pressure level (abscissa) against the 500-mb temperature difference (ordinate). A critical energy value of 10^5 ergs per gram was proposed. This method never attained popularity, not because of its computation method but because it was not an accurate measure of total available energy.

The request by the chief of the bureau for local studies on severe storms generated a large number of papers and reports during the 1950–1955 period. Some of the studies were published in the leading meteorological journals of the period. Among them were papers on instability lines by Crawford (1950) and Brunk (1953), on objective methods of forecasting tornadoes by Shuman and Carstensen (1952) and Armstrong (1953), and one by Malkin and Galway (1953) that compared the meteorological conditions associated with the hurricane tornado with those of the nonhurricane tornado.

Many other papers were received whose content was considered of value, but did not warrant formal publication. Some of these were printed in limited quantity for internal distribution as research reports of the Weather Bureau. The subjects of these reports ranged from aids for forecasting tornadoes (Kraft and Conner 1955) to composite charts of surface and upper-air features from major tornado days in five different areas of the country (U.S. Weather Bureau 1954). Others appeared in a mimeographed publication, the *Forecasting Research Bulletin,* which carried such items as objective aids for forecasting tornadoes within a state or portions of states and local checklists for tornado occurrence. The bulletin's distribution was limited to within the bureau. Some notable topics of the *Forecasting Research Bulletin* were the analysis and forecasting of the instability field (Foster 1953a) and the analysis of tornado situations (Means 1953). Also found were objective methods of forecasting tornadoes in western Kentucky and western Tennessee (Schmidt 1952) and in Ohio (Mook 1952). While the response to the call of the chief of the bureau for research papers on severe storms was very good, the quality of most of the papers was not. The primary purpose, however, to motivate those interested in severe storms to action, was attained. Time would improve the quality of the research efforts, which in turn would improve the forecasting of severe local storms.

7. The early Kansas City connection

J. R. Lloyd, meteorologist in charge (MIC) of the Kansas City district forecast office from 1944 to 1952, was described by one of his contemporaries as a man who set his own priorities and assumed that he needed no authorization from higher authority for whatever he wanted to do, whenever he wanted to do it. Since

SOME CRITERIA FOR TORNADO FORECASTING

Vertical Structure

1. LFC (MPI) 650 mb or greater over area.
2. Dry layer above a moist low-level layer at least 3000' but less than 8000' thick.
3. Means' instability index.
4. Showalter"s instability index 5 degrees C or more.
5. Increasing instability at time of tornado ocurrence.
6. Temperature inversion in the lapse rate.
7. Steep lapse rate (greater than moist adiabatic) above inversion.

Surface Conditions

8. Narrow dew point ridge extends into area with dewpoint 55 degrees F or higher.
9. Cyclonic wind shear on surface map.
10. 12-hour pressure fall at forecast time 6 mbs or more over area.
11. Location of threat área within favorable region (SE quadrant) of cyclone - especially for family types of tornadoes.
12. Signs of lifting mechanism approaching the area - squall line, front, pressure jump line, thunderstorm area, precipitation area.
13. Widespread heavy rain is unfavorable for tornado formation.
14. Large irregular 3-hourly pressure changes.
15. 3-hourly isallobaric discontinuity (may be weak) outrunning wind-shift at surface - perhaps a squall line but not necessarily showing weather. Pressure jump line and surface pressure tendency field associated with upper cold front are examples.

Upper Air

16. Low level (850 mb) moist southerly current (jet) of 30 knots or higher into area.
17. Upper level (about 14000') westerly current (jet) of dry and cooler air into area.
18. Warm advection between 5 and 14 thousand feet indicated by pibals over threat area.
19. 700 mb temperature advection pattern showing warm advection east of trough and cold advection to west of trough.
20. 500 mb isotherms diverging down-thermal-wind over the threat area 0-12 hours lag.
21. Strong 500 mb temperature gradient to west of area.
22. Cold air pocket at 500 mb to west of area.
23. Upper level (500 or 300 mb) trough to west of threat area deepening or accelerating toward area.
24. An approaching 300 mb jet maxima.

Climatolgical Aids

25. Time of day.
26. Season and geographical location of threat area.

Objective Aids

27. Kansas-Nebraska system.
28. Schmidt and Mook systems.
29. Large-scale flow of moisture toward north MSY-AMA system.

FIG. 7. Suggested criteria for tornado forecasting (after Shuman and Carstensen 1953).

the bureau was criticized by the media in Oklahoma for its lack of action in tornado forecasting and because air force forecasts were "leaked" to the public (Beebe 1984), Lloyd began to release reworded air force forecasts to the press.[2] In January 1952, Lloyd established a unit at Kansas City for the purpose of investigating and developing methods for severe storms forecasting. The techniques under consideration were primarily those of Fawbush et al. (1951) and those of Lloyd (1942). The plan was to test both methods during the 1952 severe storm season, possibly again in 1953, evaluating results and consolidating procedures before placing them for use in an actual forecast program (Hass 1952). These actions and continued criticism by the media forced Reichelderfer to action sooner than he desired and the bureau began releasing routine severe storms forecasts from the Washington Analysis Center in May 1952. After this, the work at Kansas City degenerated to forecasting tornadoes on an operational basis only within its area of responsibility and maintaining liaison with the Severe Weather Warning Center (SWWC) at Tinker AFB and the Severe Weather Unit (SWU) in Washington.

Lloyd died in August 1952; moreover, the unit he established was reduced to a one-man operation for the 1953 severe storm season. A Raob Analysis Chart was developed by Foster (1953b) that included not only data from the PI chart (LFC, mean mixing ratio, depth of the moist layer) but also the forecast hail size (Fawbush and Miller 1953), the maximum potential wind gusts in thunderstorms (Fawbush and Miller 1954), and expected turbulence (Air Weather Service 1952). The stability index (SI) computed for this chart used the mean wet-bulb potential temperature of a layer of air near the surface to determine a lifted 500-mb temperature. A proposed method of predicting the stability index field was to advect the 500-mb temperatures downstream with 50% of the 18 000-ft (or 500-mb) winds, while projecting the 500-mb lifted temperature downstream with the full gradient-level wind. The forecast stability pattern then was obtained by graphical subtraction (Sugg and Foster 1954). In the fall of 1953, a proposal to locate a severe local storms forecast center in Kansas City, while retaining the center in Washington, was submitted to the chief of the bureau by the acting MIC of the Kansas City forecast office, H. L. Jacobson. This was rejected on the basis of duplication of effort.

8. SELS research in Washington

As noted in the last section, the combination of public outcry, bad press, and congressional pressure resulted in the decision by the Weather Bureau in early 1952 to issue tornado forecasts for the public even though it had hoped to develop improved methods for forecasting tornadoes under the provisions of Public Law 657 prior to being committed to this task. On the plus side, although the Tornado Project had only progressed to the preliminary stage of its investigation, the early results were encouraging. Also, the success, although limited, of the group at the Analysis Center, which had been making severe weather forecasts for several weeks, gave credence to their procedures (Galway 1989). A memorandum from the chief of the bureau announcing this decision was sent to all first-order weather stations on 21 March 1952.

Conferences were held at the central office in Washington during the first week of April 1952 for the MICs of the district forecast offices east of the Continental Divide, the area most prone to tornadoes and severe thunderstorms. An operational plan (U.S. Weather Bureau 1952) was formulated at these meetings that included not only forecast procedures but also warning procedures. The plan included provisions for continued research and development of forecast techniques in severe local storms at the Scientific Services Division, at the Analysis Center, and at Kansas City. The Washington group of research forecasters and supervising analysts continued to release tornado and severe thunderstorm forecasts to the public until 21 May 1952, when the SWU began operations. In June 1953, the SWU became the Severe Local Storms (SELS) Center.

The initial SWU was a hastily formed group of five forecasters from the central office and field stations. Membership in this group was temporary until permanent personnel were recruited. The transition to a permanent staff took from mid-July until October. A supervisor was added to the unit in December 1952. The composition of the first permanent group was quite homogeneous.[3] College trained and relatively young, they had received most of their meteorological training while in the military, and all but one had fewer than ten years of Weather Bureau service. It was revealed later that comparatively new personnel to the bureau were intentionally selected because they were less likely to have preconceived ideas in the area of severe storm forecasting.

In October 1952, the Scientific Services Division conducted a course in severe local storms at the Analysis Center. The purpose of this course was to provide additional background for improved forecasts and intensified research (U.S. Weather Bureau 1952). The two-week course was primarily for the five forecasters in the SWU but ten field forecasters were also selected

[2] Oklahoma, at that time, was one of the states in Kansas City's area of responsibility.

[3] The first permanent severe local storms forecasters selected, and month entered on duty, were Allen I. Brunstein (October); James A. Carr (August); Joseph G. Galway (July); Robert H. Martin (August); and David J. Stowell (September).

to attend. The course included a review of the available knowledge concerning the formation, movement, and structure of tornadoes, thunderstorms, and squall lines, plus a detailed presentation of the AWS methods of forecasting tornadoes and severe thunderstorms. An update on the latest research in the areas of the pressure jump line, objective tornado forecast methods, storm detection by radar, and sferics was presented in a session on applied forecasting research. It was made obvious to the SWU forecasters that over and above their forecast duties, the development of new and improved methods for forecasting severe storms was expected from them.

The overall supervision of the SWU was provided by the supervisor of the Analysis Center, Joe R. Fulks, until January 1953, when he was replaced by A. K. Showalter. A supervisory position was authorized for the SWU. Kenneth M. Barnett was selected for the position, joining the unit in December 1952. Barnett had served as an aerologist for the U.S. Navy during World War II. He entered the Weather Bureau in January 1946 as an aviation forecaster at Kansas City and, later, served as an advisor to the Irish Meteorological Service at Shannon Airport in Ireland.

By early 1953, each SWU forecaster had selected or had been assigned an area of study related to severe local storms forecasting. An improvement in the forecasting of wind gusts, hail, and turbulence was the goal, but the initial efforts lacked the objectivity that was sought. Such things as checklists of favorable parameters for the development of severe local storms, statistical studies of the relationship of tornado occurrence to surface temperature and dewpoint fields, and the 500-mb wind maximum were developed. But none of these efforts improved upon the empirical methods of Fawbush and Miller.

Studies by Barnett (1953) and Carr (1955) would prove useful later on, but not until they had been modified. Barnett proposed a checklist for the prediction of tornadoes consisting of parameters from two charts, the potential instability (PI) chart and the tornado parameter (TP) chart. This latter chart was a checklist of related surface and upper-air parameters considered favorable for the formation of tornado activity. Among these were surface dewpoints of 55°F or more, 850-mb dewpoint of 8°C or more, 700-mb temperature less than 14°C, and a 500-mb temperature at least 26°C colder than the 850-mb temperature (a measure of steepness in lapse rate).

The parameters from these two charts gave a measure of the instability field at sounding observation time. The area defined by an LFC of 650 mb or greater from the PI chart was advected for 6 h with the 850-mb flow, while the area defined by an 850–700-mb temperature difference greater than 26°C was advected with the 700-mb flow for a similar period. Locations where these fields overlapped were thought to approximate the threat area for severe activity 6 to 12 h in the future. Favorable low- and midlevel wind fields were also required. Basically, it was an attempt to place numbers on the Fawbush/Miller empirical findings.

This semiobjective procedure was used for most of 1953 and early 1954, but fell into disuse as Barnett was replaced by Donald C. House in March 1954. However, analysis of the instability field remained an important aspect of forecasting severe local storms, and the PI chart was retained but modified and renamed the Raob analysis chart. The primary change was in the method of determining the LFC. On the PI chart, the LFC was found by lifting the average temperature of the lower moist layer dry adiabatically until it reached the mean mixing ratio of the lowest 3000 ft, then moist adiabatically until the parcel crossed the actual sounding. This intersection was taken as the LFC. For the Raob analysis chart, the procedure was modified by assuming a dry-adiabatic lapse rate in the lowest 3000 ft through the predicted afternoon maximum temperature. The point of intersection of this projected temperature with the mean mixing ratio was then lifted moist adiabatically, and where it crossed the actual sounding determined the LFC. The lifting was continued to the 500-mb level and the algebraic difference between the parcel temperature and observed temperature at 500 mb defines the lifted index (LI) as used in SELS (Galway 1956).

The paper by Carr (1955) indicated that an area of rapid increase in surface temperature during the 3-h period prior to thunderstorm activity was favorable for intense storms. If an increase of two or more degrees Fahrenheit per hour for the 3-h period was observed, tornadoes might be anticipated, provided other severe storm parameters were favorable. Figure 8 is an example of this aid. An independent study by Kuhn et al. (1958), using the climatological network of Kansas and Oklahoma from 1951 to 1955, found a marked correlation between thermal tongues or "hot spots" and the occurrence of tornadoes. They suggested that this method be adopted as a forecast tool. A desired forecast lead time of 6 h was mandated by Weather Bureau instructions, however. The first SELS releases at that time were usually around 1700 UTC. Thermal ridges and rapid temperature increases were noted and used for revisions or extensions of forecast areas.

In the summer of 1953, Barnett requested a research forecaster and a research assistant. A projected reorganization within the bureau would eliminate the research forecaster position at the district forecast offices. It was agreed generally that Robert G. Beebe, research forecaster at the Atlanta, Georgia, forecast office, having directed most of the research on tornadoes performed at that office, would be a suitable candidate for the new position. Beebe and the assistant, Georgina Neubrand, joined the SELS unit in October 1953. Up to this point, the SELS forecasters had produced 11 papers pertaining

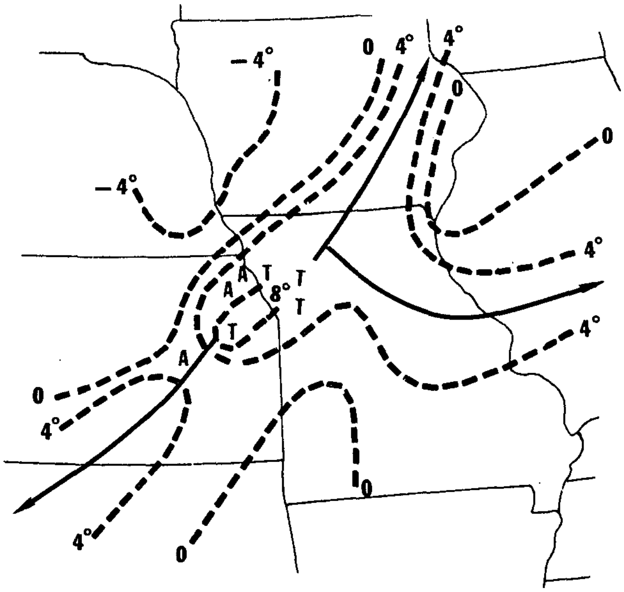

FIG. 8. Delta-T in degrees Fahrenheit, 2130–1830 UTC, 14 March 1955. Solid lines indicate thermal axis. T—tornado occurrence and A—hail, ¾ inch or greater between 2130 and 0030 UTC (after Carr 1955).

to severe local storms: six unpublished efforts that remained within the unit, four papers that were distributed within the Weather Bureau only; and one, by Malkin and Galway (1953), that was published in the *Monthly Weather Review.*

Beebe spent his first weeks meeting with various Weather Bureau people in Washington, including the SELS forecasters, and with the personnel of the Kansas City forecast office. He concluded (Beebe 1984) that

> There was a very great diversity of ideas on what to look for in tornado forecasting and, for a time, this was disconcerting. Gradually, one theme seemed to evolve and that was we were all looking for something to nearly instantly change the precedent [raob] sounding into one characteristic of a thunderstorm sounding. That is, a sounding without the low-level inversion and one with moisture to great depth in height. This did not make sense to me because my experience was that this takes time—many minutes or even hours.

His research led him to look for proximity soundings, that is, those taken no more than an hour before tornado development, within 50 miles of a tornado, and ahead of the parent thunderstorm. Beebe collected 11 soundings that fit his definition and his "study suggested that the so-called typical inversion disappeared as the time and place of the tornado approached." His results did not conform to the accepted theories and ideas of the time, that is, instant change in the precedent sounding to the thunderstorm sounding. In short, the concept was too controversial and the paper was not published until 1958. It must be noted, however, that Beebe offered no mechanism to explain "the slow change in the sounding or structure of the lower atmosphere." This would come later.

In his search for proximity soundings, Beebe noted that all tornadoes were being grouped together regardless of airmass type, geographic location, or season. He sorted the types of soundings (air masses) into four classes for a paper that was submitted for publication in 1954 but was never published. Again, the result of his research did not fit the conventional thinking of the era. An abbreviated version of this paper that dealt with the inverted "V" sounding (Beebe 1955) was printed as "Correspondence to the Editor" in the *Bulletin of the American Meteorological Society* (BAMS).

Beebe was not alone in receiving rejection slips. The paper on the SELS lifted index (Galway 1956) was also printed via the "Correspondence to the Editor" section in the BAMS. It must be pointed out that bureau personnel required central office approval before submitting papers to a meteorological journal, but there was no control over the correspondence section. During the period 1953–1957, the SELS forecast group produced 87 papers that dealt with severe local storms, of which 23 (26%) were published in some form. These 87 manuscripts do not include papers generated by the National Severe Storms Project (NSSP). By comparison, in the five years following the establishment of the National Severe Storms Forecast Center's (NSSFC) Techniques Development Unit (TDU) in 1976, the SELS unit and TDU wrote a combined 90 papers on severe local storms, of which 87 (97%) appeared in print. While some of the earlier papers by SELS personnel may not have been worthy of publication and preprint volumes were not available until the early 1960s, there is adequate evidence that changes in the status quo in the area of severe storms (nonrelease of tornado forecasts to the public) were unacceptable to some in the early and mid-1950s.

The changes in the SELS staff in the spring of 1954, while subtle, proved to be the turning point for the direction that SELS research would take, and essentially was the basis of the success of the severe storm forecasting program of the Weather Bureau. The SELS supervisor, K. M. Barnett, accepted a position with the U.S. Army Signal Corps. Donald C. House, who replaced Barnett as SELS supervisor, had previous assignments with the International Aviation Section of the Weather Bureau in Washington, as assistant regional director of region III in Kansas City, and as a district forecaster at the Kansas City forecast office. Since the Kansas City regional office worked closely with the personnel from the Scientific Services Division assigned to the Tornado Jump Project, House was familiar with the research being performed at both the Scientific Services Division and the Kansas City forecast office. House's interest in severe local storms surfaced when he wrote an article on the interpretation and prognosis of the Showalter stability index (House 1952).

When House became SELS supervisor, his mission, as stated briefly by the chief of the bureau, was to "improve severe local storm forecasting techniques and reduce forecast area size." House brought to SELS a personal enthusiasm and drive that soon was reflected throughout the staff. He accomplished one of the chief's mandates the first year. The average area size for tornado forecasts was reduced by 50%. In the fall of 1954, an ambitious development program to improve forecasting techniques began. Rather than just the layer from the surface to 500 mb being considered, as had been the practice, meteorological processes through the entire atmosphere were taken into consideration. The results established the SELS Center as a viable and respected forecast unit of the Weather Bureau by the late 1950s.

The SELS staff was increased in April 1954 by the addition of a sixth forecaster and another assistant research forecaster. The research forecaster, Ferdinand C. Bates, brought with him ideas from the work of Herbert Riehl on a configuration of jet axes and jet maxima that produced low-level (850 mb) convergence surmounted by high-level (500 mb) divergence (Riehl et al. 1952). This was a possible solution of how the typical precedent sounding (Showalter and Fulks 1943) could be transformed to Beebe's proximity sounding. A careful analysis of the wind fields at 850 and 500 mb could locate the low-level and upper-level jet axes. With an extrapolation of these positions in time, a credible tornado area could be approximated. Beebe and Bates submitted a paper on this new concept in June 1954 but reviewers who held to the theory of instantaneous change in the air mass from precedent sounding to proximity sounding were quite critical of the paper. After several rewrites, the paper was accepted and published six months later (Beebe and Bates 1955).

9. SELS research in Kansas City

The SELS unit was transferred from the analysis center to the district forecast office located at Kansas City Municipal Airport during August and September 1954. This was the result of several recommendations by the George Committee. It was the first step in the consolidation of the Weather Bureau and U.S. Air Force severe storms forecast units (Galway 1989). The transition to Kansas City went smoothly, and during the late fall and winter months of 1954–1955 various individual research projects by the SELS staff came to fruition. A group effort resulted in a manual entitled *SELS Forecasting Procedures.* This mimeographed manuscript, which outlined the general methods used in forecasting severe local storms, appeared in February 1955. The object of the manual was to acquaint bureau personnel with the charts, methods, parameters, definitions, and techniques utilized in SELS operations. It received only limited distribution, as a forecasting guides program was being established by the bureau, and it was believed that the material in the SELS manual could serve the basis for a forecasting guide.

Beebe, who played an important role in the preparation of the manual, was called upon to revise and expand the manual into a forecasting guide. He spent a considerable amount of time, including four weeks in Washington, in preparing the material. As the publication date approached, the question of authorship arose. Beebe felt that since he had written most of the guide he should be listed as author. House, on the other hand, as supervisor of the SELS Unit, was of the opinion that he should be author (Beebe 1984). The end result was that Jay S. Winston (1956) of the Extended Forecast Section in Washington was listed as "Editor" of *Forecasting Guide No. 1, Forecasting Tornadoes and Severe Thunderstorms.* This apparently minor difference of opinion was the first in a series of events that led to the dramatic separation of the research personnel from the forecast group.

There never seemed to be a dull moment during the early years of SELS's existence. If there was not an exciting weather situation to stimulate the group, there was a behind-the-scenes flap to activate the adrenalin. A successful February 1955 tornado forecast elicited a congratulatory letter from the chief of the bureau, F. W. Reichelderfer. A week later, Reichelderfer informed House that he ran across a comment that "there had not been any research papers produced by the SELS Unit since it left Washington." The chief assured House this was an unfair evaluation of the unit considering the length of time it had been in Kansas City (Reichelderfer 1955, personal communication). This did not placate House, whose response included a list of ten papers produced by SELS since its arrival in Kansas City. One had been accepted for formal publication, eight others had been submitted for review for publication, and the "SELS Forecasting Procedures" was to be available in two weeks (House 1955, personal communication). During 1955, the SELS staff produced 17 papers on severe local storms: nine were published and six presented at various meetings of the AMS.

A panel discussion on tornadoes at the November 1954 meeting of the AMS in Miami, Florida, suggested the use of an aircraft as an observational platform for securing better delineation of mesoscale features associated with the severe local storm setting (U.S. Weather Bureau 1955a). Not only did the use of aircraft for sampling the atmosphere take far fewer expenditures than the establishment of highly concentrated upper-air networks, but also, as found by the Thunderstorm Project, aircraft increased the amount of data available and resulted in a better understanding of the three-dimensional structure of the thunderstorm (Byers and Braham 1949).

In October 1955, the 140th national meeting of the AMS was held at Oklahoma A&M College (now Oklahoma State University) in Stillwater, Oklahoma. At this meeting, Clayton F. Van Thullenar, director of the Weather Bureau's Kansas City regional office, House, and Beebe met with James M. Cook, a pilot who had experience flying in areas of thunderstorm formation because he was often contracted by farming interests for cloud seeding. Van Thullenar was interested in equipping Cook's aircraft with temperature and humidity recorders, and having him fly through tornado forecast areas prior to the onset of convective activity. Other meetings followed and in the last week of November 1955, the Weather Bureau signed a contract with Cook to fly his specially instrumented F-51 airplane (Fig. 9) as an observational platform. The purpose of his mission was, as stated in the contract (U.S. Weather Bureau 1955b),

> to make observations of temperature and humidity gradients in both the horizontal and vertical plane, as well as other meteorological elements required by the Weather Bureau which were in the scope and performance of the airplane. Observations are required when feasible and practicable before, during and after the occurrence of severe atmospheric disturbances such as thunderstorms or tornadoes.

This effort, named the Tornado Research Airplane Project (TRAP), was plagued with problems from the outset. The meteorological sensors were constantly in need of calibration. Often, after flight plans had been made, the pilot or the aircraft was unavailable for various reasons (Beebe 1984). However, the aircraft was operational for 33 days from 20 April to 31 August 1956. It flew in or around some 36 tornado and severe thunderstorm forecast areas. The aircraft also flew 15 flights in July in cooperation with the Office of Naval Research and six flights in August for the University of Wisconsin. In June 1956, the aircraft made flights

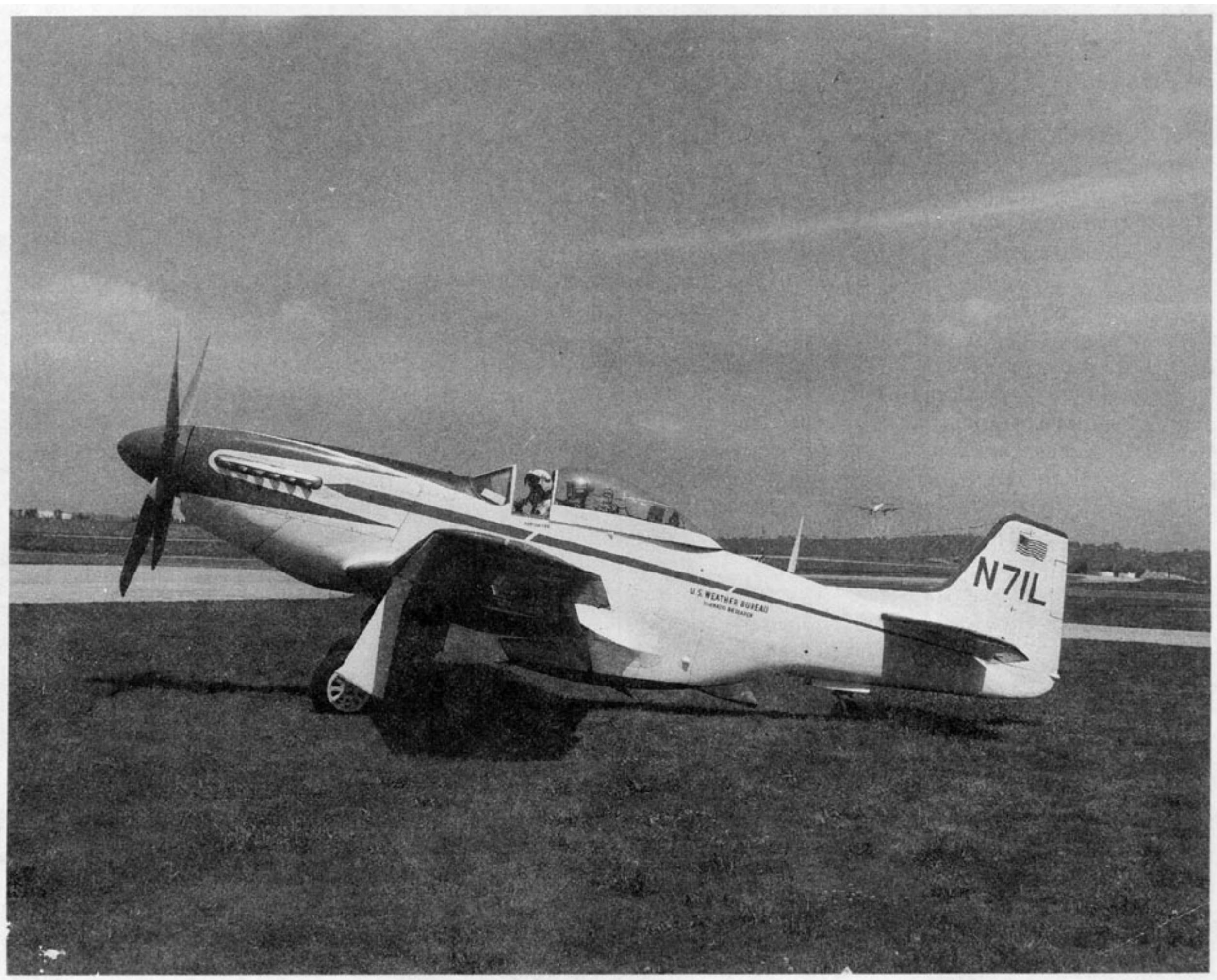

FIG. 9. F-51 tornado research airplane.

over the eastern slopes of the Rocky Mountains, where a squall line was predicted to form. Fujita (1958) presented the structure and movement of the dry front that played an important role in the development of the squall line. A summary of the first season for the TRAP was compiled by Beebe (1957).

Several extra people were hired to assist SELS research in processing the large volume of data obtained from the flights. The research forecasters assigned to the project were expected to spend 25% of their time on the forecast desk, to acquaint themselves with the current severe local storm forecast procedures and to spell the regular SELS forecasters so that they might work on their individual research projects. This did not sit well with the research forecasters, but their objections were overruled by the SELS supervisor, House. This was not the cause, however, as many at that time thought, of the rift between the research and the operational staffs.

In February 1956, Dr. Louis J. Battan of the University of Chicago was hired by the Weather Bureau as a consultant on the TRAP field program. Although the data collected during the first season of operation appeared to be quite valuable in increasing the knowledge of severe local storms, Batten submitted his resignation effective 1 August 1956. He cited a variety of reasons for his action, including the fact that the SELS supervisor headed both the forecast operations and the research functions (TRAP 1956). In response to this, the chief of the bureau directed Van Thullenar, who was appointed district meteorological officer at Kansas City in November 1955, to be the field director of TRAP. After this, there would be no formal research arm to the SELS Center for almost two decades.

The separation of the operational and research forecasters did not solve the problems of the TRAP. A mass exodus of research personnel took place in the fall of 1958. Fred Bates took a leave of absence in September to further his education. Beebe, Charles F. Chappell, and Howard H. Hanks resigned from the Weather Bureau to form a meteorological consulting firm in Kansas City. Clarence L. David transferred from the TRAP to the SELS Center in December 1958. The SELS forecast staff continued to provide weather briefing, information, and data required in the operation of the TRAP.

In the fall of 1959, the Weather Bureau initiated a program of collaboration with components of the U.S. Air Force (AF), Federal Aviation Agency (FAA), National Aeronautics and Space Administration (NASA), and the U.S. Navy (USN) in which multiple plane missions would be flown into thunderstorms and squall lines. The TRAP was renamed the National Severe Local Storms Research Project (NSLSRP) beginning with the 1960 tornado season. The specific objectives were 1) to identify and dimension the dynamic, kinematic, and thermodynamic elements of the squall line; 2) to isolate those features that determine its degree of severity; and 3) to gain any knowledge that might be used to minimize its hazards (Goddard 1962). Three aircraft from the Weather Bureau's Hurricane Research Project and three others supplied by the U.S. Air Force increased the total aircraft available to the project to seven. The original P-51 was replaced in 1958 by a P-38 aircraft. The code name given to the aircraft penetrating the squall lines was "Rough Riders," which was quite appropriate, as testified by hail damage to the aircraft in postflight photographs.

Early in 1961, Van Thullenar was named director and Dr. Chester W. Newton chief scientist for the National Severe Storms Project (NSSP).[4] They would guide the fortunes of NSSP for the next three years. There were 13 aircraft available, though not all simultaneously, and with some dedicated to special missions. The objectives of the project differed little from previous years, but from the modest beginning in 1955 with one aircraft, NSSP was engaged in one of the largest field research programs ever conceived for the study of a geophysical phenomenon (Williams 1961). In addition to the aircraft, two overlapping surface networks of automatic surface observing stations were established in 1961 to measure pressure, humidity, temperature, and precipitation. The Alpha network comprised stations 30 to 50 n mi apart, and covered Oklahoma, the southern half of Kansas, and the northern two-thirds of Texas. The Beta network stations were at intervals of 10 to 15 n mi apart in the area that lies between Oklahoma City, Oklahoma, and Wichita Falls, Texas.

The NSSP began the 1963 field operations with only five aircraft committed to the project. Also, during 1963, the Weather Radar Laboratory (WRL) was established at Norman, Oklahoma, by the Weather Bureau. These changes and rumors of additional changes forewarned the demise of the NSSP. In March 1964, the Weather Bureau announced the consolidation of the NSSP and the WRL to be named the National Severe Storms Laboratory (NSSL). Dr. Edwin Kessler, formerly with The Travelers Research, was selected to be the director. Newton left the NSSP for a post as senior scientist, National Center for Atmospheric Research (NCAR), Boulder, Colorado. Van Thullenar spent several months winding up the remnants of the NSSP in Kansas City prior to his retirement.

The NSSP preprinted a series of 22 reports pertaining to the project between 1961 and 1964. Since these reports were limited in reproduction and distribution, they did not constitute a formal scientific publication. The NSSP group based in Kansas City produced well

[4] The change in title from NSLSRP to NSSP resulted from an objection by a representative of a participating agency that NSLSRP was "too cumbersome."

over 100 manuscripts related to the project during its lifetime, many of which were not intended for publication. Approximately 20% of the papers were accepted for publication in various meteorological journals. The participating agencies handled their own data reduction and reports concerning their respective objectives.

SELS operational research was unusually productive and considerable progress was made in forecast improvement during the first four years in Kansas City. The composite chart (Fig. 10), a graphic of the major parameters associated with severe local storms, emerged as a reliable tool for the forecaster. Beebe (1984) wrote that this period was "one in which some extraordinary advancements were made in forecasting tornadoes and severe thunderstorms."

The advancements Beebe made reference to were, in part, the response to Chief Reichelderfer's mandate to improve severe local storms forecasting techniques. These included a paper on a mechanism for the release of convective instability (Beebe and Bates 1955), an assessment of the type of air masses in which tornadoes occur (Beebe 1955), and a technique for the prediction of extreme turbulence (Bates 1955). In their forecast rote, Fawbush and Miller relied on the Showalter stability index as a measure of the instability of the air mass (Air Weather Service 1952). The lifted index as developed by the SELS Center was more of a predictor than a measure of latent instability (Galway 1956). Also, during this period, a technique for forecasting hail size based upon physical, rather than empirical, reasoning was developed (Foster and Bates 1956).

In the spring of 1955, a better means for locating the upper-level jet was deemed desirable as the band of strong winds at 500 mb that had been relied upon was consistently lacking during the summer months. The "jet chart" (Lee and Galway 1958) was conceived and developed. House (1958) illustrated the difference between cold-season and warm-season vertical distribution of divergence and the different emphasis on analysis and prognosis associated with each season. At the surface, Magor (1958) documented that mesolows can, at times, be identified and tracked for several hours with the surface observational network.

10. Discussion and implication

The move to Kansas City in the late summer of 1954 was made for two reasons. First, there was pressure on Chief Reichelderfer from the press in the Midwest and plains states, areas most prone to tornadic activity, to move the SELS operations from the East Coast "where tornadoes were less common." The second reason was an order emanating from the Eisenhower Administration for all sectors of the federal government to eliminate duplication of effort. As this affected both the Air Weather Service (AWS) and the

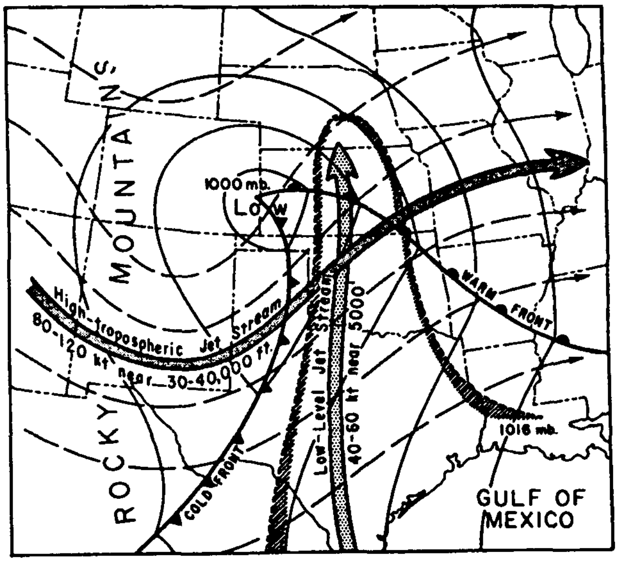

FIG. 10. Schematic features of a severe weather outbreak. Solid lines are sea level isobars; dashed lines streamlines of upper-tropospheric flow. Shading outlines general area of moist tongue in lower levels; this is in general associated with the region of potential instability (after Newton 1967).

Weather Bureau, Kansas City was selected as the collocation site. In January 1956, the collocation was consummated.

The timely receipt of radar reports was one problem common to both the SELS Center and the SWWC. A network of World War II WSR-2 and WSR-3 radars had been established through Texas, Oklahoma, Arkansas, and Louisiana prior to the formation of SELS, and more radars were in the process of being installed. The radar reports were transmitted over Service A teletypewriter system on a "time available" basis, however, so that the receipt of the data was extremely unreliable. The situation was rectified in late 1955 with the implementation of the Weather Bureau's Radar Report and Warning Coordination (RAWARC) teletypewriter system. The timely availability of the national radar reports led to the formation of the Radar Analysis and Development Unit (RADU) in January 1956. This unit collected, analyzed, and transmitted hourly summaries of these reports back to the field stations over RAWARC and into the CAA communications system. The control center for RAWARC and the RADU were collocated in the Kansas City forecast office with the SELS Center. The RADU rapidly became an important asset to SELS.

The foregoing events contributed much to the improvement of the overall operations of SELS. First, RAWARC provided a more rapid means of distributing the SELS products than by the Service A system. Second, the SELS forecaster was relieved from plotting radar reports. This freed more time for the interpretation of the data. And third, the collocation of SELS and SWWC resulted in mutually beneficial coordination between the Weather Bureau and the Air Weather Service.

In the mid-1950s, when it was necessary to replace the WRS-2 and WRS-3 radars, the Weather Bureau had a choice between the WSR-57 radar with a detection range of 250 mi or a Doppler radar, which then was in an experimental stage, that might detect a tornado up to 70 mi distant. The WSR-57 was chosen over the Doppler since it was considered more of an all-purpose radar that would meet the bureau's various needs, especially in the warnings area. In retrospect, it was the better decision. The issuance (lead) time, prior to activity, for the first forecast (watch) of the day fell into the 2- to 4-h range. Once activity had formed, radar reports were used to issue additional forecasts or revise the initial forecast area(s). The modernization of the weather service today will include both the installation of a Doppler radar network (the WSR-88D) to observe the low-level wind field and circulation, and wind profilers to measure the upper-level wind field. It is comforting to know that the small group of severe local storm forecasters 40 years ago were correct in their assessment that more, not fewer, observations of the wind field were vital in the prediction of severe local storms.

The TRAP for the period 1956–1958 was strictly a Weather Bureau operation. The role of SELS was to coordinate with members of the TRAP in selecting the most favorable area of severe storm potential to sample, if any, within the range of the P-51 aircraft. Once in the area, the pilot sent reports to SELS such as the location of the dryline, formation and growth of the thunderstorms, and similar observations of interest to SELS. These were received in real time. At times, the information received resulted in the issuance of a forecast area or a revision to an area issued prior to the flight. The data collected from the instrumented aircraft were checked, microfilmed, and made available by project personnel for those who desired to study the data. In 1959, the project expanded as other agencies became interested. Unfortunately, no new forecast methods were developed by the project or from the volumes of data obtained.

The SELS Center received its first computer, albeit outdated, in 1963, and equipment for the receipt of *TIROS VIII* satellite pictures became available in early 1964. This began a new era in the methodology of forecasting severe local storms. In time, computers expanded in speed and capacity while newer satellites depicted features such as jet streaks that could serve as triggers of a massive thunderstorm complex. Current communications systems that transport data at the speed of light have been developed and the operational implementation of equipment such as Doppler radar, wind profilers, and lightning detection systems is opening up an entire new phase for further improvement in the forecasting of severe local storms.

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