1. Introduction

Thank you, Dr. Biggerstaff. Ladies and Gentlemen, I appreciate the opportunity to talk to you about the Thunderstorm Project (TSP), as we approach the 50th anniversary of its first field season.

Perhaps it would be more appropriate if this talk were given by Dr. Horace Byers, who was director of the Thunderstorm Project. Unfortunately his physical condition prevents him from traveling. I talked with him recently, and he sends his regards. It would be appropriate for us to send him our best wishes. For this purpose I am passing around a card for your greetings and signatures.

In the spring of 1924, a young U.S. Weather Bureau meteorologist began a series of free-balloon flights from Scott Field, near St. Louis, to trace the movement of midlevel air parcels in midlatitude cyclones and anticyclones (Meisinger 1924). On the 10th flight, about 7 hours after takeoff, and near the town of Monticello, Indiana, the balloon encountered thunderstorms. Can you imagine—riding in an open basket suspended below a balloon filled with hydrogen and trailing a drag rope and radio antenna in the midst of thunderstorms? It appears that the balloon was struck by lightning. The resulting explosion killed the meteorologist (Jakl 1925). That meteorologist was Clarence Leroy Meisinger. The Meisinger Award given each year by the AMS [American Meteorological Society] commemorates the contributions of this meteorologist who became a casualty of thunderstorms.

In August 1940 a Penn Central DC-3 went down in a thunderstorm near Lovettsville, Virginia, killing Senator Lundeen from Minnesota and 24 others. At the time it was the worst accident in the history of American commercial aviation. This was not the first, nor the last, commercial airliner to go down in an encounter with a thunderstorm, but it must have caught the attention of Congress (Washington Post 1940; CAB 1940).

In July 1943 an American Airlines DC-3 crashed during thunderstorm conditions near Bowling Green, Kentucky. The Civil Aeronautics Board report of that accident should be very interesting to many attending this conference (CAB 1944). I quote:

It is reasonable to assume that the flight entered the (storm) at the planned altitude of 2000 ft (approximately 1300 ft above the terrain). . . . Within the storm, the flight encountered a downdraft. . . . Assuming that the crew maintained constant power and airspeed after striking the . . . downdraft, the airplane would have been losing altitude at a rate substantially equal to the vertical velocity of the surrounding air. . . . As a downdraft approaches the ground, its vertical velocity is necessarily checked, and the moving air fans out into a horizontal wind. . . . It is probable that by the time the aircraft had reached an altitude of 200 feet above the ground . . . the direct influence of the downdraft in forcing the airplane down . . . have disappeared. . . . (However, if we assume that) the airplane as it approached the ground . . . passed out of the downdraft into a tailwind. . . . The immediate effect . . . would have been to increase the angle of attack. . . . At the same time the airspeed would have been decreased by the velocity of the tailwind. An immediate loss of lift would have resulted. . . .

*Edited text of luncheon talk given at the 18th Conference on Severe Local Storms, San Francisco, California, 21 February 1996.
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The report goes on to stress the need to intensify efforts to study vertical air currents in thunderstorms and to analyze the behavior expected of an airplane that passes quickly from a downdraft into a tailwind. For a report issued in 1944, it sounds rather modern doesn’t it?

In the years immediately prior to and during World War II, thunderstorms were widely recognized as the most serious weather hazard to aviation. Several scientific and aeronautics advisory groups recommended research to learn more about them. One of these groups was the Subcommittee on Meteorology of the National Advisory Committee on Aeronautics. The membership of that group included, among others: Dr. Reichelderfer, chief of the U.S. Weather Bureau; Major Harry Wexler, Army Air Force; Major A. Spilhaus, Signal Corp; Dr. Ross Gunn, Navy Research Lab.; Capt. Howard Orville, U.S. Navy; Dr. Henry Houghton, Massachusetts Institute of Technology; Dr. C.-G. Rossby, University of Chicago (NACA 1945, 6).

The American Meteorological Society commemorates four of these persons through awards and/or scholarships: Drs. Reichelderfer, Houghton, and Rossby, and Capt. Orville. The latter was the father of our own Harry and Richard Orville, and the man for whom the AMS Orville Scholarship is named. These were pioneers in meteorology in this country. They helped focus attention on the need for scientific studies of weather phenomena and helped to galvanize the Congress and the Weather Bureau into action, which led to the Thunderstorm Project.

It was into this background that the Thunderstorm Project was born. It could hardly have come at a more propitious time. The end of World War II meant that for the first time suitable airplanes and large amounts of other equipment, and large numbers of trained personnel, were available for a major weather research effort.

2. Congressional action

In January 1945 Mr. Bulwinkle of North Carolina introduced into the House of Representatives a bill identified as H.R. 164, which authorized and directed the chief of the Weather Bureau to provide safety in aviation and to direct an investigation of the causes and characteristics of thunderstorms.

Section 1 of this bill reads,

Be it enacted by the Senate and the House of Representatives of the United States of America in Congress assembled, that the Chief of the Weather Bureau is authorized and directed to investigate fully and thoroughly the internal structure of thunderstorms, particularly the degree of turbulence within such storms, and the development, maintenance, and magnitude of downdrafts with a view to establishing methods by which the characteristics of particular thunderstorms may be forecast and methods by which the characteristics of such storms may be determined on visual observation from outside of the immediate thunderstorm area.

We note the emphasis on observations from outside of the storm area; in 1945 airborne radar for weather depiction had not yet been developed.

Sections 2 and 3 of H.R. 164 authorized appropriations for such a study and for the cooperation of other departments and independent agencies in carrying it out. After hearings before the House Committee on Interstate and Foreign Commerce, H.R. 164 passed the House of Representatives on 12 June 1946 and was sent to the Senate, where it was assigned to the Committee on Commerce. It is not clear to me at this time when the bill was taken up in the Senate. However, in 1948, when the Thunderstorm Project was drawing to a close, the 80th Congress, 2nd Session passed Public Law 657, the wording of which was virtually identical to H.R. 164. Legislative action to support the field operations appears to have been through the appropriations process. For the fiscal year beginning July 1945 Congress included $185,000 in the Weather Bureau appropriations to begin this study of thunderstorms.

Dr. Reichelderfer selected Horace Byers, at the University of Chicago, as director of the new project. Both Dr. Reichelderfer and Dr. Byers had had previous experiences with thunderstorms. In a 1969 letter to Prof. Bernice Ackerman, Dr. Reichelderfer tells of some of his experiences. (This letter is in the possession of the author.)

In airships and balloons, especially in the trans-ocean Zeppelin type there were many occasions when I had reason to be “trebly interested” in convective up-rushes and thunderstorms. If I were to offer an amusing anecdote perhaps it might be about the 1923 National Balloon Race when the balloon I was in won Second Place and thus qualified for the International Race out of Brussels. Why did we place? Because we got drawn into a thunderstorm, could not get out, and were carried far enough to win!
An article in the 1923 Monthly Weather Review gives several details of Reichelderfer’s flight (Samuels 1923). Lt. Reichelderfer and Lt. Lawrance, both of the U.S. Navy, took off from Indianapolis, Indiana. During the flight they passed through several cumulus clouds where they rose 600–800 ft min\(^{-1}\) in spite of continuous valving of hydrogen. In, or near by, a cumulonimbus they were carried to 18 500 ft where they remained for 30 min or more before they could descend to land near Glen Campbell, Kentucky, 25 h, 42 min, and 489 miles from their takeoff.

3. Research objectives

The earliest published report of TSP plans was by Byers et al. (1946). In that brief report we find: “We will make measurements in thunderstorms by means of aircraft, balloons, and radar, all tied together in relation to a micronetwork of surface stations. . . . We will study and probe the thunderstorm in much the same way that a zoologist studies a new organism.”

The research plan called for a vertical stack of five airplanes to make nearly simultaneous penetrations through thunderstorms occurring over a surface network of self-recording weather stations, around the perimeter of which radiosonde and radar wind stations were located. The storms were to be detected and monitored by a large surface radar, which also would provide control for the planes and balloon releases. According to Dr. J. Fletcher (1996, personal communication), Dr. Harry Wexler, a pilot and meteorologist in the Army Air Corps, was a major force in shaping the operational plans.

The planes penetrated the storm at five different levels, 5000 ft apart (5000, 10 000, 15 000, 20 000, and 25 000 ft). The objective was to obtain the maximum number of traverses through each storm and to sample storms in all stages of development. No storm was to be avoided because it appeared too big. Storms were detected and followed, and the airplanes controlled and vectored, using a large ground radar located near the operations area. Continuous photography of the radar scopes provided information about the storm as well as locations of the planes.

I am sure that most of you will recall that the project was located near Orlando, Florida, during the summer of 1946 and at Wilmington, Ohio, during the summer of 1947 (Fig. 1). These locations were selected on the basis of thunderstorm frequencies and the presence of military facilities capable of supporting the project. In 1986, under the motivation and guidance of Mr. Dan Smith, National Weather Service, Fort Worth, Texas, a highway marker calling attention to the project was erected near the site of the 1946 operations (Fig. 2).

The immediate environments of thunderstorms in Florida and Ohio were documented by taking measurements from six SCR 658 radiosonde stations and four SCR 584 radar wind stations located around the

Fig. 1. Maps showing locations of Thunderstorm Project surface networks in Florida and Ohio.
horizontal surfaces as the balloons rose together around cumulus clouds and thunderstorms. These data allowed calculation of divergences and horizontal cloud inflow.

At the 55 surface stations we recorded rainfall, station pressure, temperature, dewpoint, wind direction, and wind speed, all at 5-min time resolution. Figure 7 shows one of the surface stations in Ohio.

4. Project aircraft

For storm penetrations the Army Air Force provided a number of Northrup P-61C-type airplanes, commonly known as the Black Widow (Fig. 8). Although originally built as night fighters, a number of these planes were converted to weather reconnaissance duty. As I recall, our planes came from a weather reconnaissance group being deactivated in the Aleutians. The P-61s carried a crew of two or three. They were built to withstand strong maneuver loads. They had what the airplane engineer would call a stiff wing, which allowed for more accurate gust measurements. Each plane was equipped with a transponder that allowed recording the plane’s position on each sweep of the radar.

One of our project P-61s is currently being restored by the Smithsonian Air and Space Museum, Silver Hill, Maryland. Another is in the Air Force Museum at Wright-Patterson AFB [Air Force Base, WPAFB] near Dayton, Ohio.

Engineers at NACA [National Advisory Committee for Aeronautics] Langley Field equipped the planes to measure airplane responses to turbulence and vertical air currents. The planes themselves were the sensors of storm turbulence and updrafts/downdrafts, hence the need for a stiff wing. But, as we all know, pilot control can induce aircraft accelerations and altitude changes. Power settings and control positions were continuously recorded, and the pilots’ panel was photographed. To obtain valid measurements, NACA requested that the pilots trim their planes for straight and level flight before entry and to use a minimum of

Fig. 2. State of Florida highway sign marking the location of the Thunderstorm Project in Florida.

perimeter of the surface network. Figure 3 shows the tracking antenna of a 658 radiosonde system. The radiosonde receiver (Fig. 4) was located inside a Quonset hut (Fig. 5). Figure 6 shows one of the SCR 584, 10-cm, 250-kw radars that was used to track balloon-borne corner reflectors to obtain radar winds. The project had four such radars in 1946 and five in 1947. These radars also were used to back up the large 10-cm ground radar. In the two seasons combined we made 824 radiosonde flights and 503 radar wind flights.

By making simultaneous releases from several stations, using similar balloon ascent rates, we obtained temperatures, dewpoints, and winds on quasi-
control inside the storm. Roughly this translated into attitude but not altitude control. Portions of flight records where there was evidence for pilots' actions that would compromise the data were discarded and not used in the analysis.

Some of the project advisors were of the view that it was not possible to make meaningful measurements of air temperatures inside the clouds. In spite of this advice, we tried. Pat Harney built a simple housing to shield the temperature element from contact with large cloud drops and rain drops (Fig. 9). After testing it in the cloud and icing tunnels at Wright-Patterson AFB, we mounted one on each of the planes. In spite of the crude nature of our air temperature system we could easily see that the updrafts were warm and the downdrafts cold, with respect to the storm environment.

To explore smaller cumulus clouds, the project employed an instrumented AT-6 and an instrumented Kytoon. One of the lesser-known aspects of the Thunderstorm Project was the use of sailplanes to explore cumulus clouds and thunderstorms. The Soaring Society of America provided three Pratt Reed TG-32 two-place gliders under contract to the Weather Bureau (Fig. 10). This group flew a total of 141 flights, several of which were into mature stage thunderstorms. On 25 July 1946, Paul Tuntland set a new national altitude record by spiraling up inside a thunderstorm updraft (Raspet 1947). Some of you will recall that Paul was later killed while soaring in the Sierra Wave.
5. Data obtained

We now turn to a few statistics about the storms studied in Florida and Ohio. [For a more complete summary, see White (1946, 1948); Byers and Braham (1949).] A total of 179 storms were selected for detailed study. The P-61s flew a total of 76 thunderstorms evenly divided between Florida and Ohio for a total of 1362 storm penetrations and 70.3 h inside thunderstorm clouds. The maximum radar top of a storm flown was 56,000 ft, and the modal height was between 35,000 and 40,000 ft. The maximum updraft encountered was 84 ft s\(^{-1}\), or about 26 m s\(^{-1}\). The maximum downdraft was about 55 ft s\(^{-1}\), or about 17 m s\(^{-1}\).
Storm turbulence and vertical air motion data were reduced and analyzed at the NACA Langley Lab. Analyses of other kinds of data, and the integration of airplane data with sounding data and surface measurements, were carried out in Chicago during the winter of 1946/47 and from October 1947 through May 1949. During the latter period the project headquarters was located on the top floor of the Museum of Science and Industry in Jackson Park.

6. Three-stage thunderstorm cell model

We used a case history approach to combine the airplane data with other types of data to elucidate the internal structure of thunderstorms. As I listened to the initial flight in Florida, I realized that no provision had been made to record conversations between the pilots and the radar controller, nor to conduct postflight interviews of the flight crews, and as a consequence, that it would be very difficult to reconstruct the flights after the fact. Steps were immediately taken to correct these deficiencies in the operations. In this way we obtained the time–space framework for each flight for later case history–type analyses.

During the winter of 1946 in Chicago, I built a Tinkertoy gadget that allowed me to position aircraft data in three dimensions, superimposed on a map of surface weather data. Using this device, and with the help of Mary Ellen Thomas, navy aerologist, I quickly realized that the storms flown on this project typically were composed of several individual cells, each of which went through a life cycle that could conveniently be divided into three stages (Byers 1948). The first stage, when the cell was dominated by an updraft, I called the cumulus stage. As the storm strengthened, a downdraft developed adjacent to the updraft. I called this the mature stage (Fig. 11). After about 20–30 min this transitioned into a final stage containing only a weak downdraft.

I first presented this model of thunderstorm cells at the spring meetings of the American Meteorological Society.
7. Effects of thunderstorms on aircraft in flight

Several studies were directed at the effects of thunderstorms on aircraft in flight (Braham et al. 1948; Braham and Pope 1949; Byers and Braham 1949, 133–145). As indicated in H.R. 164, downdrafts at low levels constitute one of the major thunderstorm hazards. The maximum downdraft measured at 5000 ft was 30–40 ft s\(^{-1}\), or about 11 m s\(^{-1}\). Fifty-eight percent of the downdrafts traversed at 5000 ft, in Ohio, displaced a P-61 by more than 500 ft. Measurable downdrafts were found as low as 500 ft above ground level in Ohio. Low-level wind shear was recognized as a potential hazard for landing aircraft, but we did not see the transition of the industry into heavy jets where wind shear became a major problem.

The P-61 crews reported hail on about 10% of the passes at midlevels in Ohio. Figure 12 shows a P-61 nose cone, which had collapsed under the impact of hail and snow. Occasionally the hail was rather large, causing 2–3-in. dents in prop spinners and other leading edges (Fig. 13). Twenty-one times the planes were struck by lightning, with only minor damage.

In an important study, NACA scientists analyzed the airplane turbulence data to see how the total variance in aircraft gust loads was partitioned between altitudes within the storms, planes, and pilots. There was a clear indication that the frequency of encountering gusts stronger than about 20 ft s\(^{-1}\) increased with altitude in thunderstorms (Braham and Pope 1949; Tolefson 1948), was independent of which plane made the measurements, and was very dependent upon which pilot was flying (Press 1948). Other studies by NACA covered such important topics as the relation between horizontal temperature gradients and vertical gust velocities (Press and Thompson 1949).

8. Other significant findings

Midlevel inflow into thunderstorms was clearly recognized and its magnitude calculated (Byers and Hull 1949); as well as the fact that much of the air in a downdraft comes from the updraft (Braham 1952). The water and energy budgets of typical Ohio thunderstorms were calculated (Braham 1951, 1952). We found that entrainment of environmental air into the updraft resulted in updraft lapse rates that are greater than wet adiabatic and set the stage for double-action energetics, with warm updrafts and cold downdrafts.

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**Fig. 12.** Hail- and snow-damaged nose cone of a P-61 after a flight through an Ohio thunderstorm.

**Fig. 13.** F. White pointing to hailstone dents on a P-61 propeller spinner after a flight through a hailstorm in Ohio.
The tilt and movement of thunderstorms were related to the vertical shear in the environmental wind (Byers and Battan 1949). The diurnal distribution of thunderstorms over the peninsula of Florida was related to the role of sea breezes from both sides of the peninsula by Byers and Rodebush (1948).

The RHI radar data obtained on the Thunderstorm Project were analyzed by Lou Battan to show that the coalescence process was responsible for precipitation initiation in many midlatitude summertime convective clouds, even though the cloud tops may have been many thousands of feet above the freezing level (Battan 1953).

Several analyses were focused on thunderstorm weather occurring near the earth surface. Previously, I mentioned some of the major surface weather phenomena given particular attention in our analyses. Included in these were such things as the mesolow under the updraft; the mesohigh under the downdraft; relations between surface rain rate, surface pressure anomalies, and surface wind divergence; the thunderstorm outflow or gust front, which Harry Moses called “the first gust”; and the humidity dip. Measurements of rain temperature were reported by Byers et al. (1949).

There are several important aspects of thunderstorms that we did not recognize. We did not recognize a weak echo vault, nor a supercell, even though they may have been present in the data. Perhaps my preoccupation with developing the cell model prevented me from recognizing it. Also very little progress was made on the electrical aspects of thunderstorms.

9. Demonstration of radar for storm avoidance

One of the most important findings of the Thunderstorm Project, in my opinion, was the demonstration that radar could be used to detect, and guide airplanes around, the most dangerous parts of thunderstorms. Today this is routine; but we must recall that during World War II radar was new, highly classified, and essentially limited to the military. Some military planes carried small radars for locating ships, submarines, and other airplanes. Large ground radars, such as we used on this project, were in use for airplane and missile tracking. Our project showed that severe turbulence and strong up/down motions were concentrated within the thunderstorm cells, while the interstitial cloud was essentially free of turbulence, and that it was possible for an adequately trained pilot, in a suitable plane with weather radar, to penetrate thunderstorms while minimizing the risk of encountering severe turbulence and strong vertical motions (Press and Binckley 1948; Braham and Pope 1949). There is no question but that this demonstration helped to motivate industry to develop weather radars suitable for aircraft use. Dave Atlas was one of the major players in that development.

10. Thunderstorm Project scientists

Now I want to turn to the people who planned and carried out the project. Every person involved in the Thunderstorm Project in any of its phases—planning, procuring of facilities, field operations, analysis of data, and reporting of findings—was vital to its success.

Actual operations and analysis of project data were carried out mainly by a group of young meteorologists fresh out of the military. They found in this project an exciting way to transition from military to civilian meteorology. A large number of these people subsequently rose to the top of their specialties. Of 66 persons involved in observations, analysis, and reporting, 13 were women—a surprisingly large number in view of the time period involved. Nine of the 66 subsequently were elected president of the American Meteorological Society. Except for those with the Soaring Society and those in the military, all project people were employees of the Weather Bureau. It is my recollection that as their work on the project came to an end, most, if not all, were given a chance to transfer to other activities in the Weather Bureau.

In the final phase of the project we microfilmed all data records and every chart and diagram and sent both the originals and the microfilms to the Data Center in Ashville.

Shortly after we had submitted the project final report to the Government Printing Office, Professor Jack Workman, of the New Mexico School of Mines, visited the University of Chicago. He reported on their research on the electrical charge separation accompanying the freezing of dilute aqueous solutions and how that processes (which has come to be called the Workman–Reynolds effect) might help to explain charge separation in thunderstorms. He invited me to join his group at Socorro, New Mexico, which I did in the summer of 1950. We had hopes that by combining findings from our project with those from the Socorro
group we might make progress on the tough question of thunderstorm charging.

The idea was simple enough. Based on their laboratory studies, freezing of weak aqueous solutions containing ammonium ions showed a reversal of the normal sign of separated charge. If the Workman–Reynolds effect were involved in charge formation in thunderstorms, and if we could release a large quantity of ammonia gas into a thunderstorm, it should invert the main dipole and be detectable in details of lightning strokes. Lightning signatures would be recorded using a network of gradient change meters. A radar would be used to monitor storm movements and coordinate the experiment.

One slight problem—how do we get the ammonia into the storm? As I recall, Dr. Workman contacted Mrs. Frances Wheadon of the Signal Corps, who arranged for a B-17 to be flown to Socorro. Into the bomb bay we fitted several large ammonia tanks, which were hooked to an exhaust tube running out the tail. I helped Steve Reynolds lay out a network of gradient-change instruments on a flat area north of Socorro. On a summer day in 1951 the radar detected storm clouds moving toward the surface network. We requested the plane to take off. Now was our chance to make history.

Another slight problem—while taxiing out for takeoff, the plane slipped off the narrow taxiway and became stuck in deep sand. Slight problem number 3—how to get a B-17 back onto the taxiway at a small field in the desert far away from facilities for jacking and moving large planes? After borrowing wingjacks and other appropriate equipment from an air force base, the plane was put back on the taxiway and readied for the experiment.

Later we had a second chance. The plane took off and was vectored into an appropriate position. The field mill network was up and running. The plane released the ammonia. Slight problem—the lightning signatures gave no indication whatsoever that the ammonia had had any effect on the charge configuration of the storm. As Steve Reynolds used to say, “Another beer experiment.”

Our time is up. I will make no effort to summarize the advancement of our understanding of thunderstorms from the time of the Thunderstorm Project to this conference—suffice it to say that the contributions made by those of you in this room truly are mind-boggling. The tools you have developed and the things that you have learned make our efforts on the Thunderstorm Project look antiquated indeed. I salute each of you and thank you.

Acknowledgments. My sincere thanks to Dan Smith, Headquarters, Southern Region, National Weather Service, for assistance with the luncheon talk and in the preparation of this manuscript and for the photograph of the Thunderstorm Marker. The photograph of the P-61 came from the Air Force Museum, WPAFB, with the help of Hugh Morgan. I also thank Jim Swinnich (National Soaring Museum), Sherry Grandjean, Marshall Billingslea, Gwen Berry, Matt Rhodina, Frank Bebedetto, and William Tinsley for help in finding historical data used in this paper.

References

In the June 1996 Bulletin article, “A New Global Water Vapor Analysis,” by David Randel et al., a production error caused the Internet address on page 1244 to be printed incorrectly. The correct address is http://wwwdaac.msfc.nasa.gov/. The Bulletin apologizes for any inconvenience this error may have caused.
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American Meteorological Society

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