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NATIONAL SEVERE STORMS PROJECT

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The Development of Aircraft Investigations of Squall Lines from 1956-1960

by

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THE DEVELOPMENT OF AIRCRAFT INVESTIGATIONS OF SQUALL LINES FROM 1956-1960

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1. INTRODUCTION

The thunderstorm, with its associated severe weather phenomena, presents some of the most intriguing practical and theoretical problems in meteorology. The Thunderstorm Project, with field investigations conducted jointly by the Air Force, Navy, National Advisory Committee for Aeronautics (NACA) and the Weather Bureau in 1946 and 1947, increased immensely the amount of data available for thunderstorm research. A better understanding of the three-dimensional structure of the thunderstorm below 26,000-ft., and particularly its internal cellular structure, was a major result. With field operations conducted in Florida and Ohio, the Thunderstorm Project was not in a position to investigate the severe thunderstorms and severe weather phenomena associated with the Western Plains squall lines [9].

With the establishment in 1952 of the Severe Local Storms Forecast Center (SELS), and following a panel discussion on tornadoes at the November 1954 American Meteorological Society meeting in Miami, Florida, renewed attention was focused on the severe weather problem [28]. Needed was adequate sampling on the meso- and microscales. Several suggestions as to highly concentrated aerological station networks were rejected because of the prohibitively high cost involved. The suggestion acted upon placed heavy emphasis on aircraft sampling supplemented with data from regular surface and aerological stations. A suitable aircraft, properly instrumented, flying pre-planned patterns in severe weather areas, would provide a flexible and economical means of acquiring the intensive observations needed. The need for a skilled pilot with an understanding of convective weather was fulfilled by Mr. James M. Cook, who had obtained considerable experience flying in areas of severe thunderstorms while carrying out cloud seeding contracts with farming groups.

2. THE 1956 TORNADO RESEARCH AIRPLANE PROJECT [7], [35].

A contract, signed November 23, 1955, called for Mr. Cook to furnish a North American "Mustang", P-51 aircraft (fig. 1), to be instrumented by the Weather Bureau, and to make meteorological observations within the scope and performance of the aircraft. Mr. Cook's headquarters was to be at Kansas City, with the flights to be conducted under the direction and briefing of the SELS Center there.

Instrumentation.- The instrument installation was conducted by Dallas Aero Service under the direction of a Weather Bureau technician. By working closely with the contractor's engineers, CAA inspectors, and having direct supervision over the aircraft maintenance personnel, the Weather Bureau technician was able to have the installations pass final inspection in time for operations in Spring of 1956. Because of time and instrument space limitations, only stock meteorological and electronic equipment was used, and custom hand-fitted installations were made. The instruments installed were:

1. U. S. Weather Bureau infra-red hygrometer.
2. Naval Research Laboratory vortex thermometer.
3. Gunn electric field meter.
4. Kollsman aneroid pressure sensing system with an electric transducer.
5. NACA Velocity-Gust-Height (VGH) Meter.
6. 16-mm. time-lapse camera for cloud photography.
7. 35-mm. time-lapse camera for photographing instrument panel.
8. 16-mm. motion picture camera with a tri-lens turrent for photographing special phenomena.
9. Two 2-channel Brown self-balancing electronic strip chart recorders.
10. Ampex Model 600 tape voice recorder.

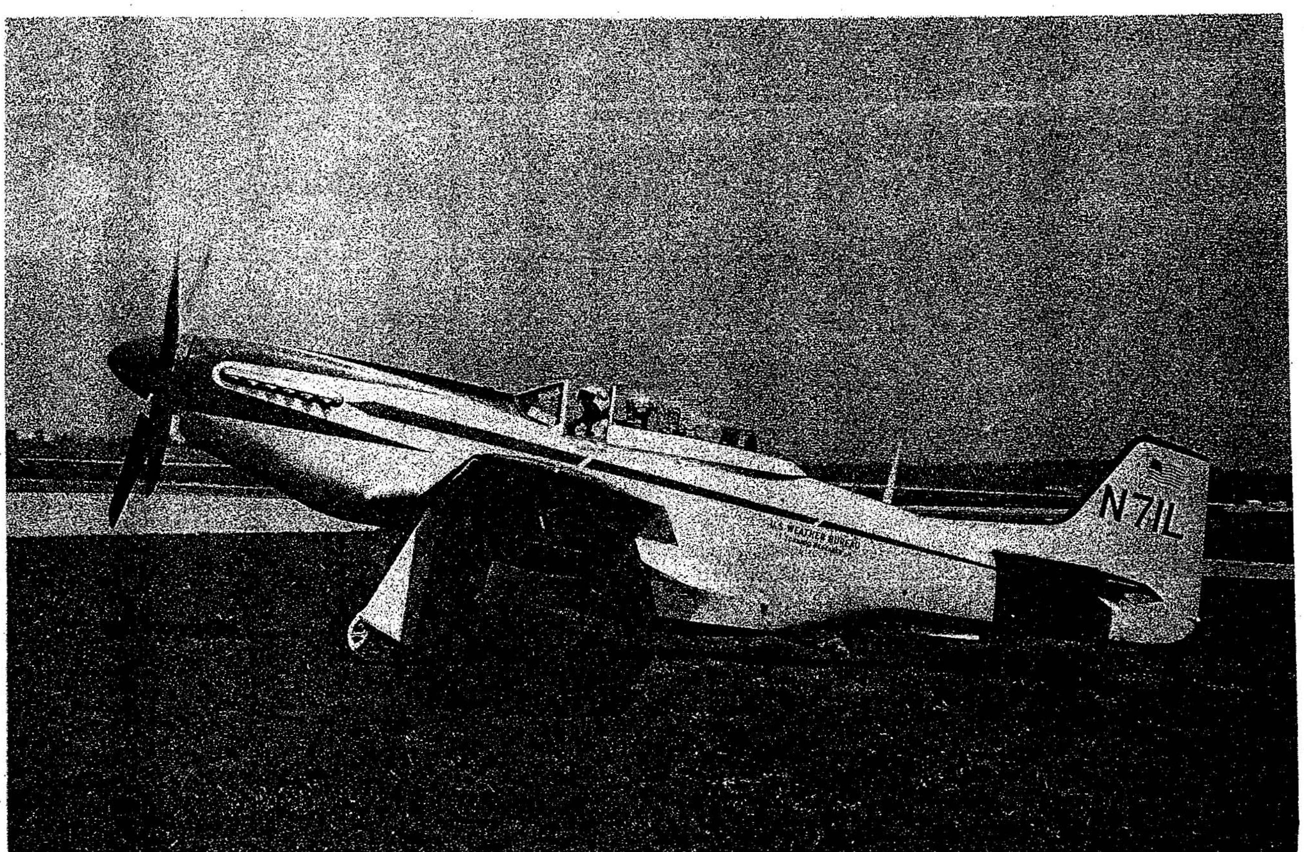


Figure 1. The P-51 "Mustang" Aircraft.

All instruments were ground and flight checked and calibrated [11]. Twelve test flights were made, including three in which the aircraft made a spiral climb around an ascending radiosonde instrument. Comparison of aircraft vs. radiosonde observations was obtained and used as an indication of the accuracy of the aircraft instrumentation. The design probable maximum errors in calibration of the infrared hygrometer ranged from about ± 0.1 gm./m.^{3} at 1-3 gm. water vapor content to ± 0.5 gm./m.^{3} at 10-20 gm. moisture content, with time lag of 20 seconds. Spot checks of aircraft data against raobs at various constant pressures showed the hygrometer indicating lower dew points by 1-3° C. than the raobs when the dew points were greater than 5° C. In the case of a rapid change to very dry air, the hygrometer was more sensitive and showed dew points as much as 15° C. lower than the radiosonde. Checks against surface observations at times of landing and take-off indicated the hygrometer was 1-2° C. lower. Ascents around radiosondes showed the algebraic mean of the deviations of the aircraft dew points from the raob data was -0.3° C. and the mean of the magnitude of the deviations was 1.4° C.

The vortex thermometer had a range of -90° C. to +50° C. with a lag coefficient in the range of 10-20 seconds. Spot tests of temperature in level cross-country flights against interpolated raob data usually showed agreement within ± 1.0° C. Ground checks during take-offs and landings showed very close agreement, usually within less than 1° C. A summary of the raob ascents showed a mean algebraic difference of +0.4° C.

The pressure sensing system had a maximum cumulative error of ± 3.2 mb. or approximately 90 feet at sea level. Ground checks of pressure at landing and take-off at fields of various elevations indicated satisfactory results.

Meteorological information was recorded in analogue form on the Brown recorders, with referencing, time, and event marks being provided for. The instrument panel was photographed every 15 seconds. Through a switching arrangement, the tape recorder could be made to record either the pilot's remarks, or incoming radio messages, or both, at the pilot's discretion.

<u>Objectives and Operations</u>. - The 1956 TRAP's over-all objective was to investigate the feasibility of using an airplane as an observational platform for securing a better delineation of mesoscale and microscale features related to the tornado setting. Objectives of each individual flight were varied from time to time for comprehensive coverage of a number of weather patterns.

There were 71 flights from which useful data were obtained. These included 36 flights into 30 severe thunderstorm forecast areas, some of which included forecasted tornadoes, and 4 flights in the vicinity of non-forecasted thunderstorm activity. Horizontal traverses at 850 and 700 mb. and spiral soundings between surface and levels up to 500 mb. constituted the majority of the flight patterns. There were 15 flights in New Mexico in cooperation with the Office of Naval Research and the New Mexico Institute of Mining and Technology. In conjunction with the University of Wisconsin and Project Prairie Grass, 6 flights were conducted in Nebraska.

Data Processing. - The data processing consisted of:

1. Making a verbatim, then an edited, transcript of the voice recorder for each flight.
2. Synchronizing the two chart rolls and extracting data in 1-min. intervals (equivalent to 4 n. mi. at the average air speed). Temperature was read to 0.1° C., humidity to the nearest half ordinate (from 0.5 gm./m.^{3} at 18 gm. to 0.05 gm./m.^{3} at 1 gm.), and pressure to 0.5 mb.
3. Scanning of photopanel film, extracting and tabulating navigational data (compass heading, omni-range bearings, ADF bearings, air speed, and altimeter) and time, correlating them with the chart time.
4. Plotting of flight track, noting times, significant events, and entering camera shots.
5. Preparing a flight summary consisting of objectives, general area of flight, approximate flight path, occurrence of severe local storms, forecast area issued, malfunctions of the instruments (if any), interesting observations and other aspects of the flight.

VGH drums were sent to NACA for development and processing. Data obtained from NACA consists of times of significant accelerations, maximum accelerations measured in "G" units, and number of accelerations in various "G" ranges. No routine processing was done on the electric field meter data.

Positioning of the aircraft was considered of greatest importance and was done by pilotage (that is, reported times over readily identified geographical points); by pilot's visual contact; by radio aids consisting of VOR bearings, ADF bearings, and pilot's reported times over radio aids when IFR; and by dead reckoning (projecting track using photopanel data and observed or estimated winds).

A flight package consisting of flight summary, flight track, edited flight transcript, and data tabulation was prepared and microfilmed for all flights, as were the original recorder charts and navigational data. These films are on file with the National Severe Storms Project, (NSSP) in Kansas City.

The 1956 TRAP was an excellent introduction to low-level aircraft probe research in squall-line environment and the particular problems involved. The practicability of using an aircraft as an observational platform was established. It was clearly indicated that the limit of sampling with the present type of instrumentation was mesoscale.

3. THE 1957 TORNADO RESEARCH AIRPLANE PROJECT [34], [36].

A conference for reviewing the 1956 TRAP and recommending plans for future operations was held in Kansas City on October 31 and November 1, 1956. Discussions revolved around the suitability of the aircraft type, the instrumentation of the aircraft, the planning and conducting of flights, and the value of the data obtained [33]. Drawing upon the recommendations of this conference and other planning conferences held subsequently, and upon the previous year's experiences, extensive detailed plans were made for the 1957 season. In December, Mr. C. F. Van Thullenar was appointed as Field Director of the Project.

In addition to the instrumentation held over from the 1956 season, there were added two 35-mm. cameras (one to photograph the horizon to determine aircraft roll and pitch, the other to take aerial photographs for navigational and wind computational purposes), an aspirating thermometer, another omni, and a complete synchronization system tying together the recorders, tracking cameras, photopanel camera, and voice recorder. An extensive testing and calibration program was planned but, for the most part, had to be abandoned due to delays in instrument installation. The radiosonde comparison flight gave good results [2], [3]. The vortex thermometer was found to have a mean deviation of +0.8° C. from the radiosonde and the root-mean-square deviation was 1.0° C. Dew point was found to have a mean deviation of -4.9° C., with a root-mean-square deviation of 5.5° C.

The general objective was to study the spatial distribution of the meteorological parameters in the most active part of the squall line. Emphasis was placed on pre-activity stages, and some of the individual flights were made to sample parameters to be used in testing hypotheses on squall-line formation. Flight patterns consisted of horizontal traverses perpendicular to the squall line, and vertical soundings extending to 400 mb. [1], [37], [38].

The success of the 1957 season was severely hampered by instrument difficulties and engine failures, which resulted in the aircraft being out of commission for an appreciable part of the season. A large part of the data obtained was not useable. The season terminated on July 7 when the airplane crash-landed at Topeka after an engine failure.

In all, 39 flights were conducted, of which only 12 provided meteorological research data. Although the small number of successful flights was disappointing, the 1957 season was not considered to be a fair indication of the value of the project in severe storm research. Tornadoes or funnel clouds were reported near 10 flight paths, and 11 flights were in SELS forecast areas. Flight packages of the useful flights were prepared for this season as in 1956, with improved post-navigation due to the use of dual omni.

4. THE 1958 TORNADO RESEARCH AIRPLANE PROJECT [16], [41].

The disabled P-51 was replaced by a Lockheed "Lightning" P-38 (fig. 2), resulting in greater range, larger instrument pay load and two-engine operation for greater safety. The P-51 meteorological instruments and recorders were modified and installed. The installation of a remote, artificially lighted photopanel solved the problems caused by obscuration by the pilot's head and natural lighting fluctuations which occurred in the previous seasons.

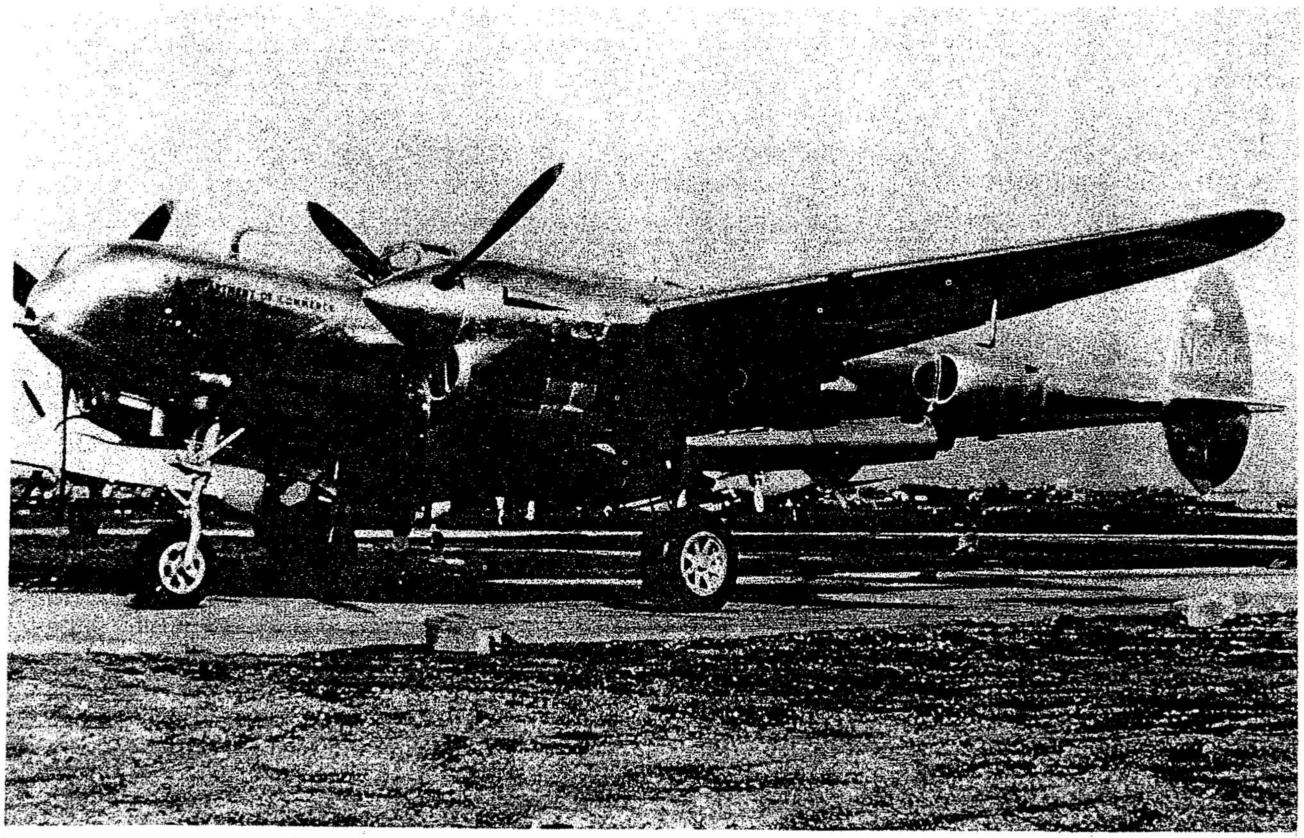


Figure 2. The P-38 "Lightning" Aircraft.

Along with the carry-over instruments, there was added on to the photopanel an artificial horizon and turn-and-bank indicator, the electric field meter, indicator lights to show when the omni and ADF were tuned and reliable, a clock with sweep-second hand, and a Veeder-Root counter. An electric clock simultaneously actuated the Veeder-Root counters on the photopanel and the pilot's instrument panel, and pens on each of the Brown recorders.

An extensive series of calibration flights based upon the previous years' plans were conducted at Topeka on March 12 to 15. This included speed calibration runs on reciprocal tracks at a low elevation over the runway, covering a range of true air speed from 140 to 210 kt. These speed runs, timed by both ground and air-borne observers, indicated an accuracy of true air speed within about ± 3 kt.

Radiosonde comparison flights were made on March 14 and 15 and on June 16. These flights indicated a mean difference in a range of approximately 0.5° C. to 1° C. between the aircraft vortex thermometer and the radiosonde temperature. A mean difference of about 2° C. was found between the readings of the infrared hygrometer and dew points from the radiosondes. By comparing the results of ascents and descents of the aircraft through a quasi-uniform layer of air, lag coefficients were found to be about 17.1 seconds for the vortex thermometer and about 7.3 seconds for the aspirating thermometer. Detailed analyses of these calibration flights are on file at NSSP.

The general objective continued to be sampling the space distribution of meteorological parameters associated with tornadoes, severe thunderstorms, and squall lines. Flight paths were patterned after the 1957 operations, with more emphasis given to sampling at the 500-mb. level. The flight planning and control, data processing, and analysis were conducted by a new consolidated research unit at Kansas City under the direction of Mr. Van Thullenar. In the area of flight planning, close liaison with SELS was maintained.

Recovering from the disastrous 1957 season, the TRAP attacked its problems with renewed vigor. The aircraft change-over was smooth and resulted in an increase from 65% to 87% in the time the aircraft was available for operational use. In addition to 26 tests flights and 23 ferry flights (8 of which included sampling in operational weather), there were 24 operational flights, of which 12 were in the vicinity of squall lines. The flight packages, containing tabulated data sheets, flight path, edited transcript, flight description, and flight profile were prepared and are filed at NSSP headquarters. Operation of the instruments, with the exception of the infrared hygrometer, was satisfactory. Several excellent flights traversing squall lines provided good research data.

5. THE 1959 TORNADO RESEARCH AIRPLANE PROJECT [16], [17].

With a minimum of instrument changes in the P-38, the 1959 season was begun. The 1958 infrared hygrometer was exchanged for a more stable model late in the season with generally satisfactory performance. The 16 mm. nose camera was modified so that a clock image was superimposed on the film. Due to gear trouble, the camera was inoperative during the latter part of the season. An HF transmitter was installed to permit ground-air communications. Radiosonde comparisons indicated about the same deviation of aircraft from raob temperatures as in the 1958 season, except that there was evidence of a probable pressure lag affecting vertical sounding temperatures.

During the 1959 season, emphasis was placed on measuring the time-rate-of-change of meteorological parameters. This included making soundings over radiosonde stations 3 hours before and after the scheduled noon soundings, in addition to soundings midway between raob stations at the time of scheduled observations. Also emphasized was horizontal sampling at the 850- and 500-mb. levels before and after the formation of convection, in order to complete data for a model of the various stages of squall-line development.

There were 8 test flights, 2 ferry flights, and 29 operational flights, two of which included soundings made in advance of and behind a squall line, and within 25 miles and 2 hours of reported tornado occurrences. One synoptic-scale low center and several mesohighs were sampled. Two penetrations of pressure-surge lines which produced severe clear-air turbulence were made. The installation of the HF equipment permitted the receipt of meteorological data for immediate operational planning and gave the ability to request changes in flight patterns whenever desirable.

The flight package was enlarged to include flight profiles of constant-pressure-level flights with adiabatically adjusted temperatures, significant points in data sheet, and the addition of pilot remarks on profiles. The IBM 650 electronic computer was used to do the data reduction computations [14]. Despite a limited number of severe weather days, the last TRAP season was successful.

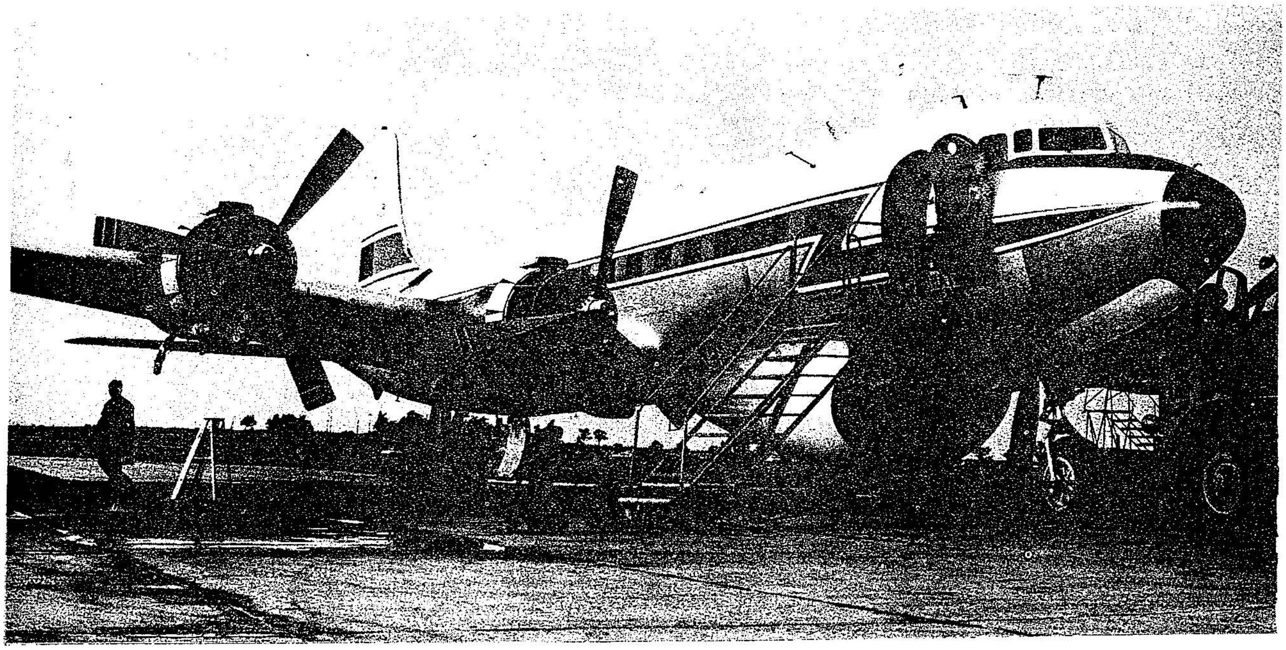
6. THE 1960 NATIONAL SEVERE LOCAL STORMS RESEARCH PROJECT (NSLSRP). [23], [24]

The firm establishment of an aircraft as an instrumental platform for severe storm research, and the acquisition by the Weather Bureau of aircraft for hurricane research, led to an expanded effort in 1960. Working within the general framework of the 1955 Washington conference, specific plans were prepared for the Project at conferences held in Washington, D. C. in September 1959 and in Kansas City in December 1959 [21].

The operating personnel of the groups participating in the 1960 operations held conferences in March 1960 [22]. The groups involved were: U. S. Weather Bureau, National Aeronautics and Space Administration (NASA), Federal Aviation Agency (FAA), Wright Air Development Division (WADD), Geophysics Research Directorate (GRD), Air Defense Command (ADC), Air Weather Service (AWS), and the U. S. Navy.

Five aircraft participated in "Rough Rider," the air-borne phase of the Project: the former TRAP P-38, one of the National Hurricane Research Project (NHRP) DC-6's (fig. 3), and a T-33, an F-102, and an F-106 of the Air Force (fig. 4). The P-38 instrumentation was unchanged from 1959. Instrument calibration tests were made by NASA Lewis Laboratory at Cleveland, Ohio, in March of 1960. Radiosonde compatibility flights were not flown in the 1960 season. The T-33 (instrumented by NASA), the F-102 and the F-106 (both instrumented by WADD) measured:

1. Pitch, roll, and yaw velocities.
2. Air speed.
3. Normal accelerations.
4. Attitude
5. Altitude.
6. Air temperature.



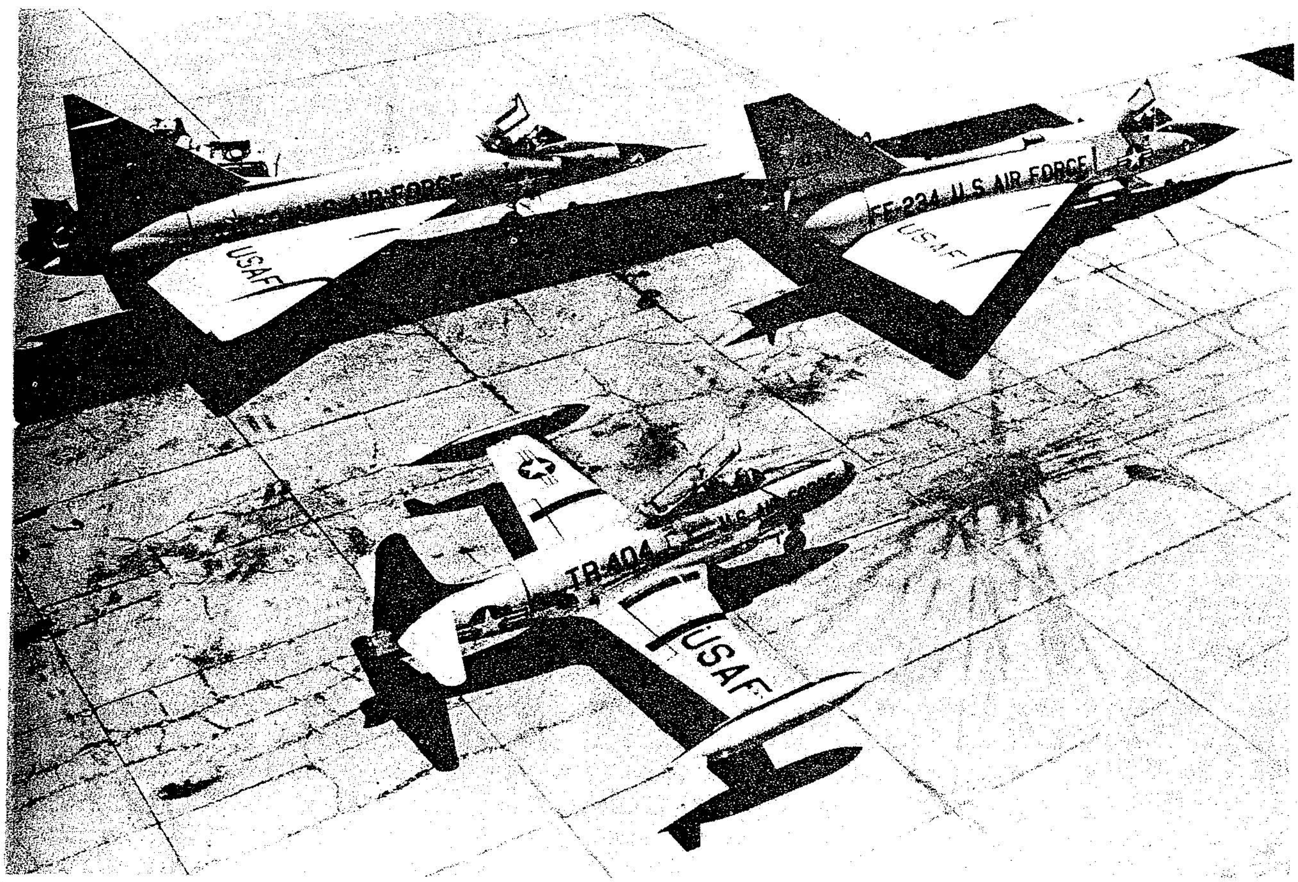


Figure 4.- The T-33, F-106, and F-102 of the Airforce

Additional parameters measured by the T-33 were: angles of attack and side slip; lateral and longitudinal accelerations; and pitch, roll, and yaw angles. The F-102 sampled ice crystal concentrations. Both the F-102 and F-106 measured engine performance and had aboard the NASA V-g (Velocity - acceleration) recorder. The Air Force aircraft were based at Tinker Field with the DC-6 and P-38 at Will Rogers Field in Oklahoma City, Oklahoma.

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; (3) to gain any knowledge that might be used to minimize its hazards.

The objective of the Air Force and NASA involving use of the T-33 was to collect basic data on thunderstorm structure and associated weather phenomena at all altitudes for the purposes of:

1. Solving problems in areas of structure and engine operation of present-day aircraft.
2. Providing basic design criteria for future aircraft.
3. Helping to develop the best methods for thunderstorm penetration.

The F-102 was to evaluate procedures, developed earlier under simulated conditions, for F-102 thunderstorm flying, and to conduct general thunderstorm research with delta-wing aircraft.

Objectives specifically evolving out of F-106 operational problems were:

1. To determine suitable thunderstorm penetration procedures at altitudes above 20,000 feet under all operational conditions, including penetrations at supersonic speeds.
2. To determine operating characteristics for the engine/duct combination under conditions of high altitude and high ice-crystal concentration.
3. To correlate aircraft response with information on storm structure obtained by a fully instrumented T-33.

The daily operational planning and weather briefings were conducted in the Operation Office in the Flight Operations and Air Worthiness Laboratory, FAA Center, located on the west side of Will Rogers Field. The jet aircraft were controlled and vectored by FAA controllers, using information from the ADC radar and the WSR-57 radar with attenuator circuits.

Communications between the two radar sites, operation headquarters, SELS Center, the research unit, and Fort Sill were accomplished by a leased "hot line" telephone. Ground-air contact was maintained by both VHF and UHF radio. Air-to-air contact utilized UHF channels. Flights of the P-38 were handled as in previous years. Soundings and traverses in the squall-line environment were the dominant flight plans. The DC-6 was similarly handled and used primarily for radar coverage. Selected stations were requested by RAWARC for serial rawinsondes taken 90 minutes apart. Photo-rockets were to be launched from Fort Sill and notification of launch time given by the "hot line"; however, no launchings were made.

A more extensive data collection was undertaken in 1960. The P-38 made 34 operational flights. The data were assembled into flight packages as in previous years, the flight profiles being machine plotted. Plots of the 55 aircraft soundings were made. The T-33 made 20 flights with 62 penetrations in the 15,000 to 40,000-ft. altitude range. It encountered hail in 6 penetrations. The F-102 conducted 12 flights with 19 penetrations in the 35,000 to 45,000-ft. range at subsonic speeds. The 15 penetrations during 14 flights of the F-106 were in the 38,000 to 42,000-ft. range, at both subsonic and supersonic speeds. The raw data from the Air Force aircraft were reduced by NASA and WADD and the reduction was expected to take at least one year. Flight descriptions, unedited transcripts, and debriefings from all aircraft, as well as in-flight, hand-copied observations and radar film for two flights of the NHRP DC-6, are on file with NSSP, Kansas City.

The aircraft data were supplemented with regular and special data collections. Regular, special, and serial rawinsonde and regular pibal observations were taken at Weather Bureau and Air Weather Service conventional and mobile stations. Data from the Severe Local Storms Research Network were added to the conventional surface observations. Radar coverage was provided by the Weather Bureau and ADC sites. Sferics and satellite data were collected. The cases of May 4 and 19 have been completely assembled and microfilmed by the National Weather Records Center (NWRC) and are available as two separate packages [32], [33].

The successful 1960 season saw most of the 16 severe weather occurrences (within a 150-mi. radius of Oklahoma City) in May sampled. The close teamwork of the operative personnel and a minimum of aircraft outage for maintenance made this possible. Difficulties were uncovered so that corrective action could be taken in planning future operations. The use of two radars with different beam-width characteristics for control of penetration aircraft was found undesirable. Improvement in quality and quantity of scope film from Weather Bureau and ADC radar was needed. The season did point out the tremendous opportunities in severe weather sampling available and the proper means of acquiring these data.

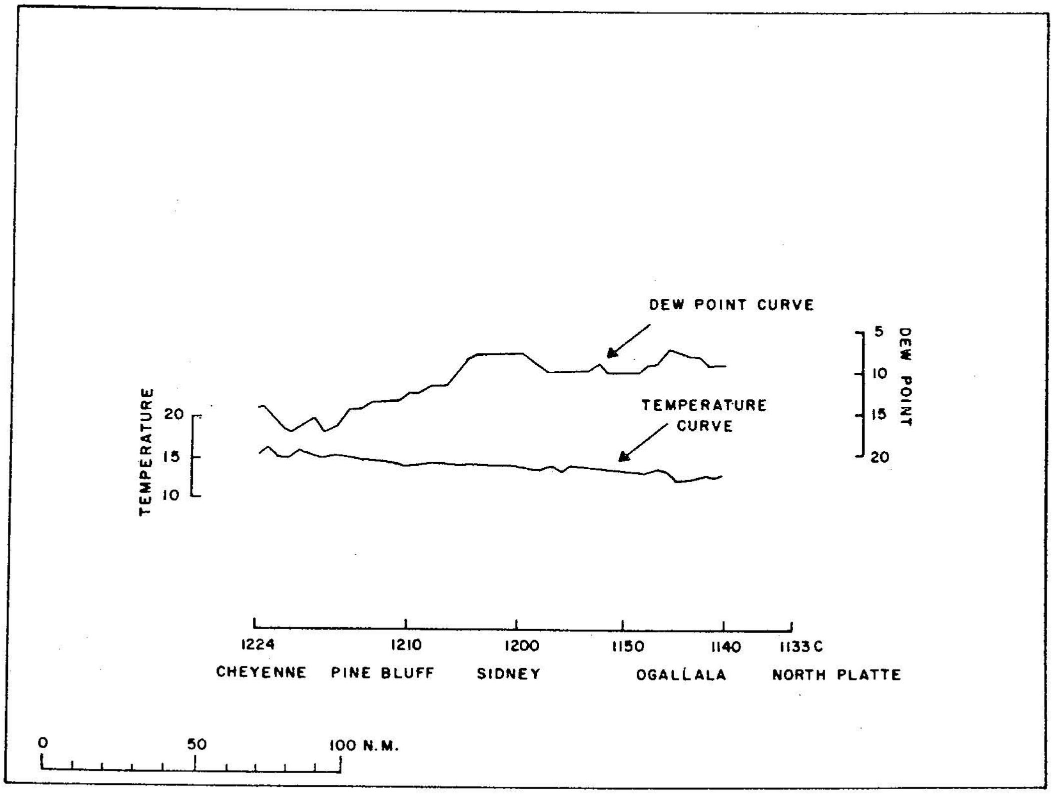
7. RESEARCH UNDERTAKEN

At the time of the Project's conception, it was known that certain general spatial and temporal distributions of synoptic-scale parameters were conducive to the formation of severe weather. Evaluated for the most part qualitatively, these parameters, such as divergence, vorticity, and stability, served as groundwork for the severe weather forecast on an areal basis. However, the major production of severe weather is conducted on a sub-synoptic scale. The mesoscale aircraft data, made more valuable by the mobility factor, provide quantitative measurements of parameters such as moisture and heat, and permit the study of the thermodynamics, kinematics, and dynamics, such as vertical motion, detailed air-mass structure, and its modification rate, etc., necessary to produce severe weather. Case studies of separate weather situations involving TRAP flights were begun on a restricted basis, due to a limited staff, in 1957. These studies gave valuable leads as to the areas into which more extensive investigations should be made. The content of the studies, and other reports, will be touched upon briefly to illustrate the type of information obtained. A full interpretation of the results is beyond the scope of this paper.

The flights of June 11, 1956, in the Wyoming-Nebraska border area furnished data for separate studies by Beebe [8] and Fujita [13]. A strong dew point "front" and a moderate instability line development were investigated. The 700-mb. traverses (fig. 5) indicate an increase in moisture in the area of the developing instability line outside the rain area. The increase was attributed to vertical motion after an inspection of the 700-mb. charts ruled out horizontal advection. Several waves with lateral dimensions of 30 to 50 n. mi. are indicated in the moist air. Using the flight transcript, recorded visual observations suggested a close association between a band of cumulus and the wave of greatest amplitude. The vertical structure of the dew point "front" (fig. 6) shows an eastward tilt of the front of as much as 1/30.

The location and intensity of temperature and moisture intrusions and their associated gradients in relation to the synoptic pattern are very important in severe storm forecasting. Investigation of these gradients was undertaken in 1957 by Hanks [15]. Using 10 of the 1956 flights during the summer months, some intense moisture (dew point) gradients, on the order of 5° to 10°C/4 mi. were found at 700 mb. The maximum observed during that period was greater than 10°C. in 20 seconds (approx. 1 mi.). Dew point gradients more intense than temperature gradients were observed in frontal traverses, which is indicative of the summer season. Observed elongated moisture tongues with strong gradients on the western side resulted in a westward location of the moisture axis when compared with SELS operational analyses. The SELS temperature analyses agreed quite well with the TRAP data. Aircraft observations of clouds and turbulence on 700-mb. traverses appear to be correlated with passage through the strong gradient on the western edge of the moist tongue. Frequently these moisture gradients do not extend to the surface, as found by McGuire [20].

Rawinsonde soundings have been an important phase of TRAP and NSLSRP. Used in series from one, or more than one station, they have provided data for time and space cross sections. Such a set was taken at Omaha, Nebraska, on June 21, 1957. Taken before and after a squall line passage, certain anomalous features, indicated in (fig. 7), were uncovered in the analysis by Williams [39]. The cold spot and superadiabatic lapse rate near 400 mb. at 2045 CST is not reflected in either of the soundings on the sides. This anomaly can be accounted for by the passage of the sounding balloon in and then out of a cloud, yielding the colder wet-bulb temperatures. The existence of the anomalous warming above 600 mb. just prior to the line is supported by



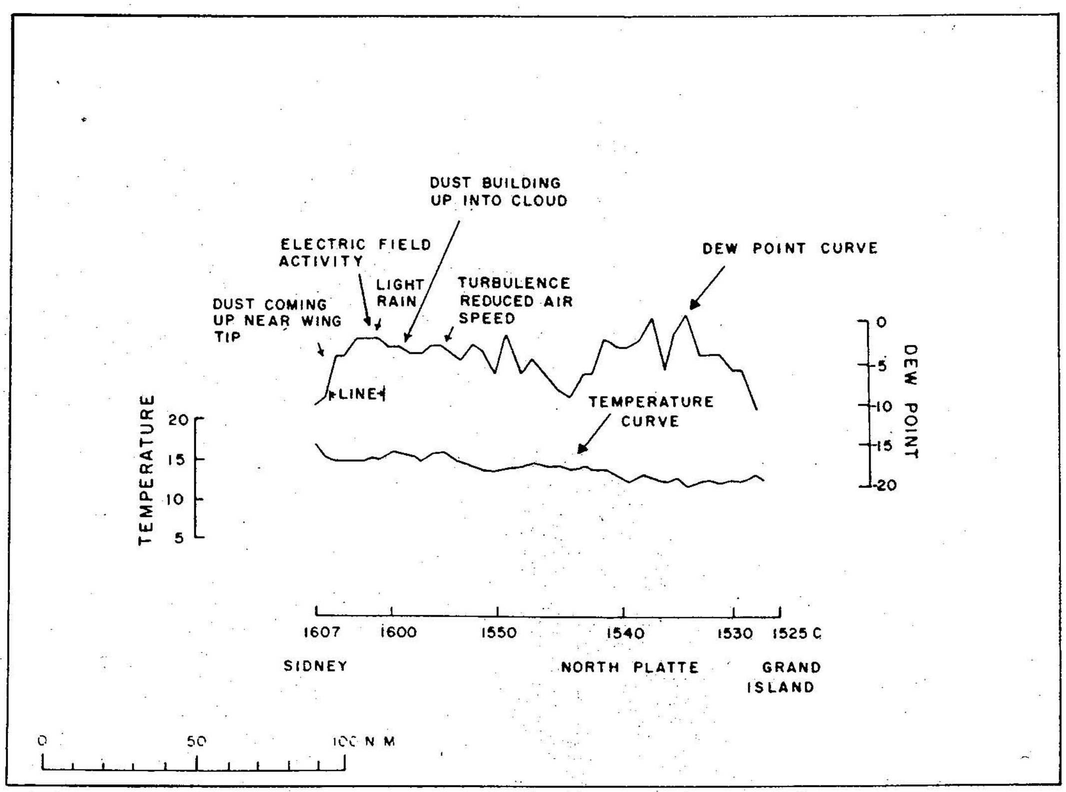


Figure 5.- 700-mb. profiles of the TRAP flights of June 11, 1956.

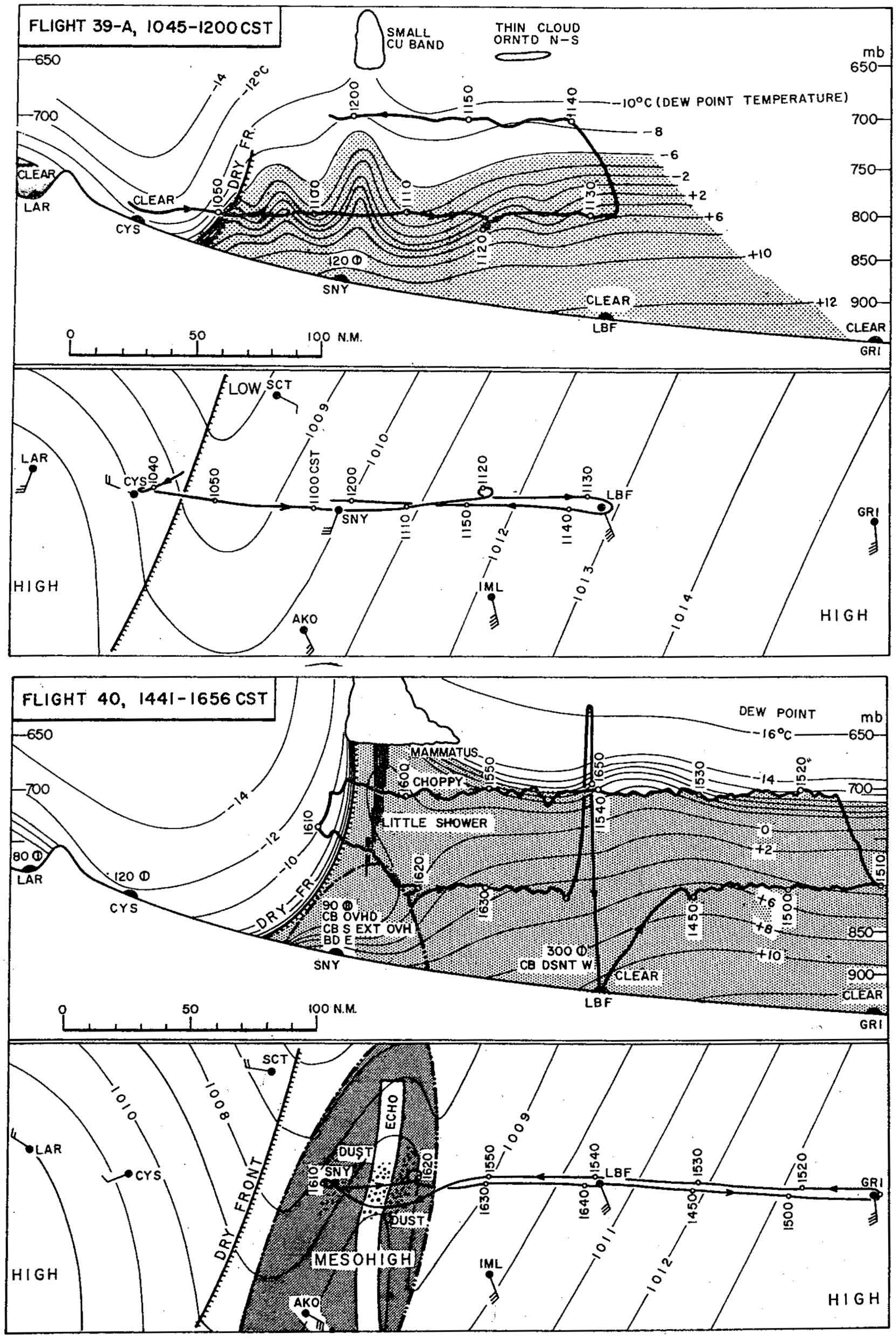


Figure 6.- Cross sections and mesoanalyses of June 11, 1956 case. (Reprinted with permission of T. Fujita.)

the data from three soundings. Similar cases have been observed on tornado special soundings requested by SELS. The infrequent observations suggest the phenomena are mesoscale in extent. The simple subsidence explanation of the anomaly is contradicted by the high moisture content of the layer. The occurrence of a funnel cloud within 3 mi. and 27 min. of the 2045 CST sounding suggests a relationship.

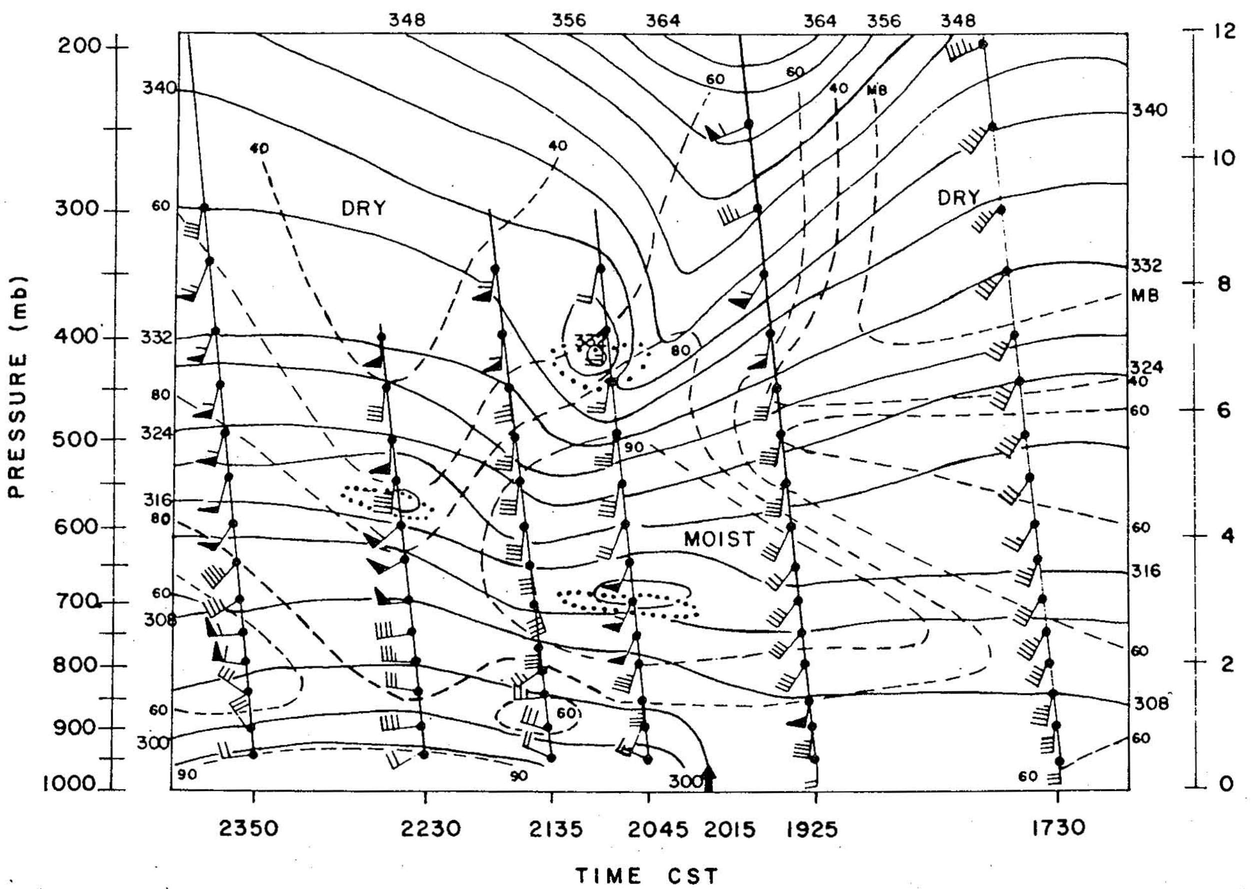


Figure 7.- Vertical time cross section of potential temperature, wind, and relative humidity at North Omaha, Nebraska, June 21, 1957. Time positions of the soundings slope with time at a rate of approximately 3 1/4 min./km. Isentropes are drawn as solid lines for every 4°K. A dotted line is used to enclose regions where the temperature lapse rate is superadiabatic. Isopleths of relative humidity are drawn as dashed lines for every 20%, except that the 90% isopleth has also been added. The time of squall line passage at the surface is shown by an arrowhead.

The aircraft's ability to sample short-period time changes and complement the rawinsonde data in time and space is illustrated in figure 8. From a study by Lee and David [18], the moisture increase and cooling at 850 mb. in advance of the squall line is pictured by four traverses between Oklahoma City and Tulsa. The squall line, producing large hail and tornadoes, passed Oklahoma City near 1600 CST.

By the end of the 1959 season, the sample population had increased sufficiently that pilot studies could be begun on the structure and development of squall lines. A study conducted by Lee and David [19] utilized flights which traversed an incipient, inactive, or active squall line, or those which were in close proximity to a squall line. The

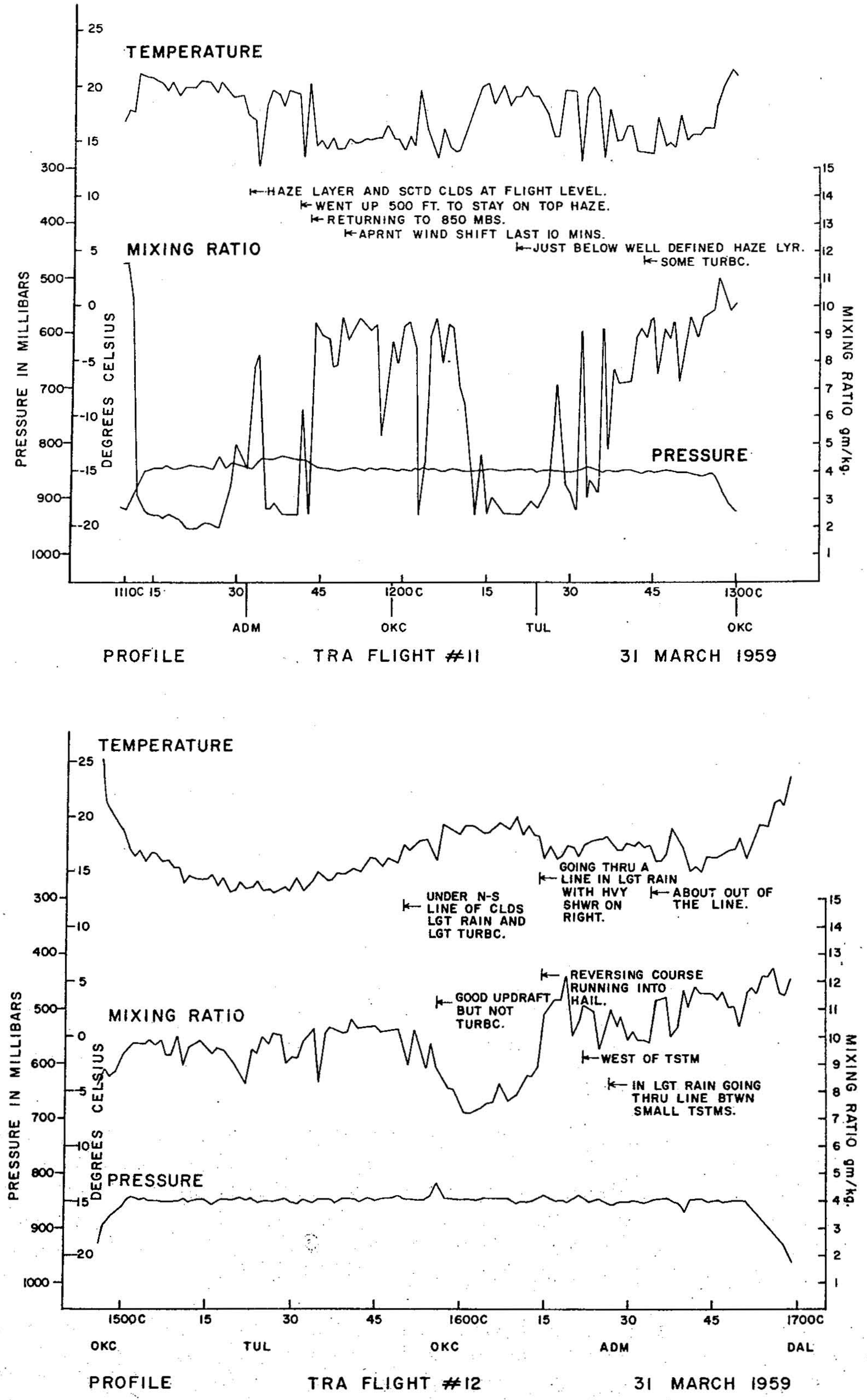


Figure 8.- Profiles of TRAP flights on March 31, 1959.

traverses through lines are made in the clear air between the cloud towers and over the tops of clouds, to avoid aircraft hazards and obtain meaningful temperature data.

Mean profiles were constructed from these traverses and classified as to pre-line-formation, cumulus, or thunderstorm stages (fig. 9). A warming and drying at 850 mb. to the rear of the thunderstorm line and a moisture pull-up to 700 mb. only in thunderstorm stages was indicated. Mean soundings constructed and analysed for each stage indicated the overturning effect of the squall line as it moved and propagated through an air mass.

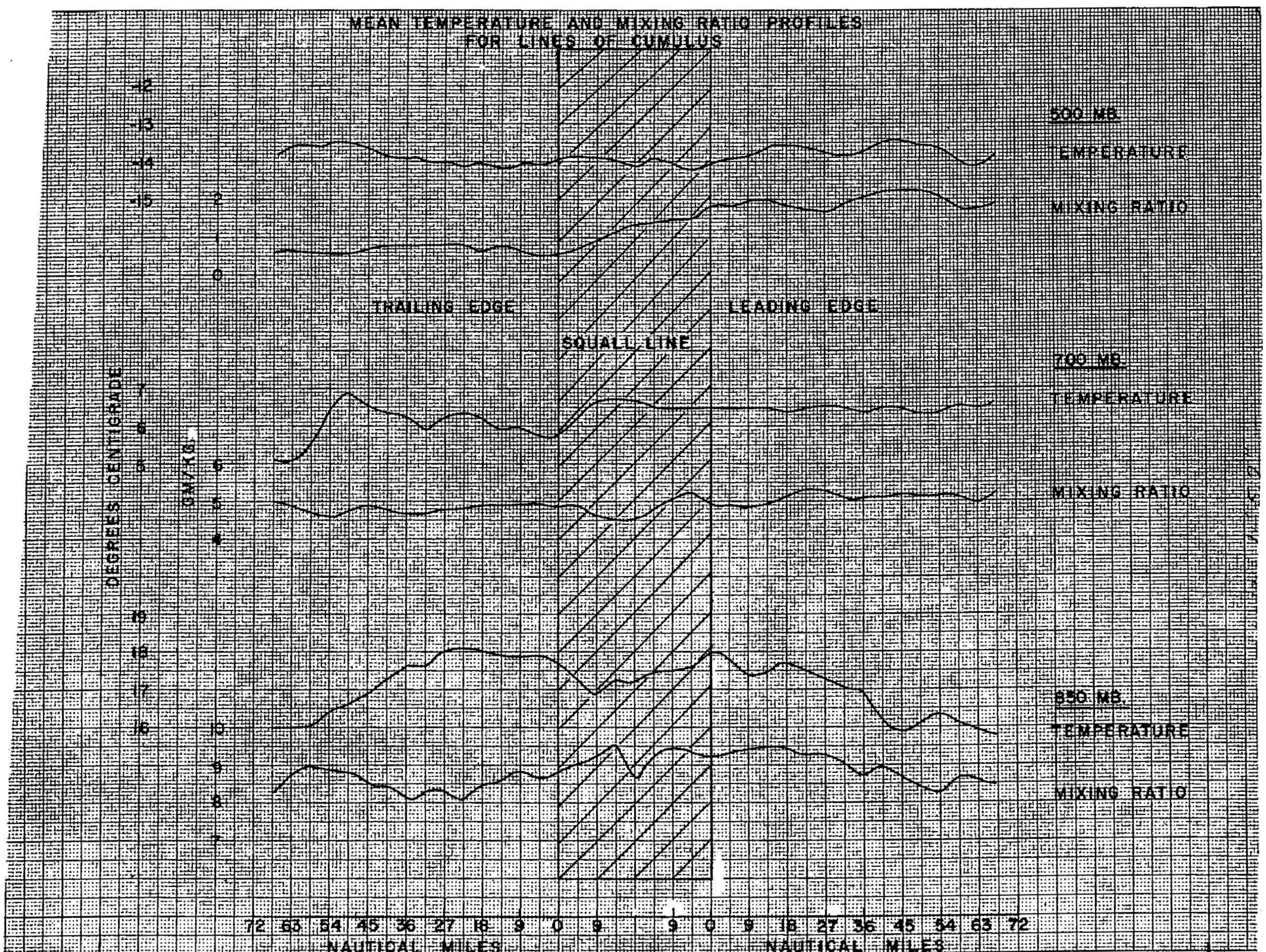


Figure 9.- The mean profiles of the cumulus stage.

There is a surface dew point discontinuity frequently observed in the proximity of squall lines. Not being either a warm or cold front, it has been designated "dew point front" or "dry line" by severe weather personnel. Two 1959 flights provided data for an investigation by McGuire [20] into the dimensions of the dew point front. Sixteen traverses, (11 are shown in fig. 10), were made at various levels from 940

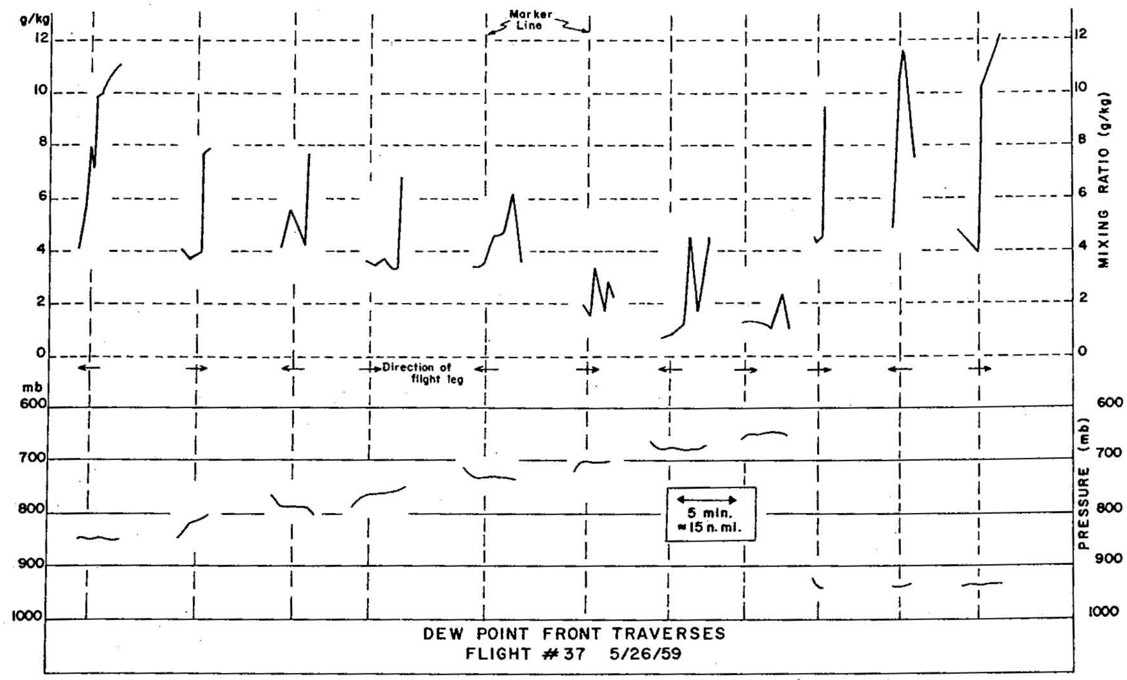


Figure 10.- Mixing ratio and pressure profiles of dewpoint front traverses.

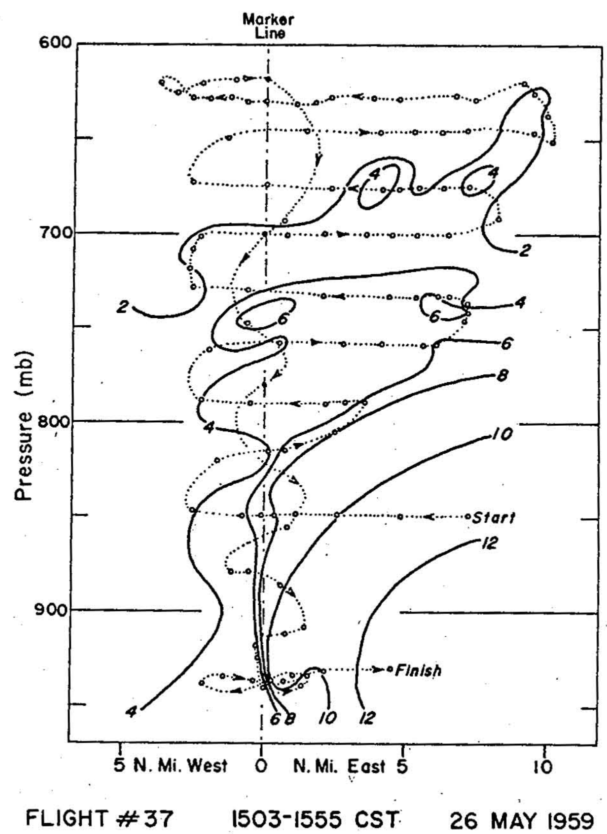


Figure 11.- A mixing ratio vertical cross section of a dew point front. Dots and arrows indicate flight path.

to 760 mb. through the front. The vertical dashed line in the figure is a geographically located point. The front was nearly vertical for the first 150 mb. above the ground; then it sloped toward the moist air (fig. 11). An analysis of virtual temperature indicates little change as the front is crossed.

The vertical, spiral aircraft soundings were an important part of the observational program. The total number of soundings was 180, of which 24 were used for test purposes. A study utilizing this data was conducted by Williams [42]. Prepared were space and time cross sections of the potential temperature and moisture distributions in the environment of incipient, active or dissipating squall lines (fig. 12). The most significant finding was the downward slope of the isentropes from in back of the line toward the leading edge. This sloping occurred at higher levels in the incipient stages, at most levels in the active stage, and only intermediate levels during the dissipating stages. There was indicated a possible relationship between the level of occurrence and degree of sloping, and the intensity and development of the squall line. The moisture, abundant and stratified ahead of the inactive line, becomes less stratified as the activity increases. When the cross sections are combined with horizontal traverse data, the squall line zone, (leading edge marked in fig. 13), appears as upward bending of the isentropes superimposed on the general downward slope of the isentropic environment.

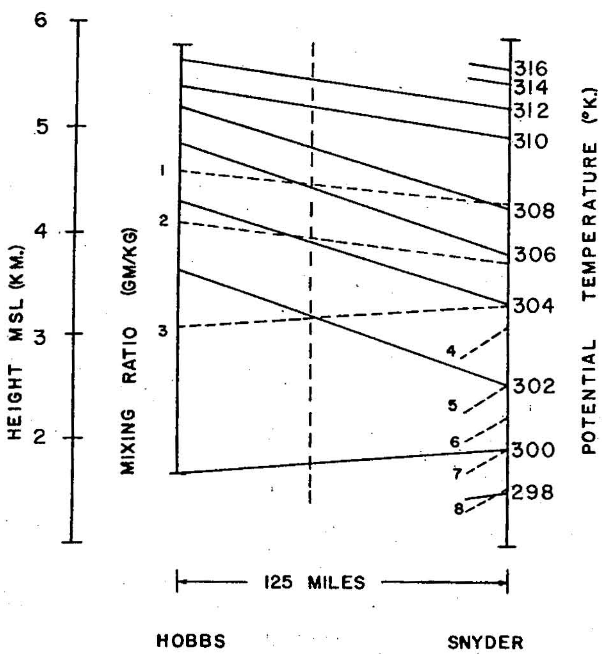


Figure 12.– Cross section of potential temperature across an active squall line. The dashed line is the leading edge of the squall line.

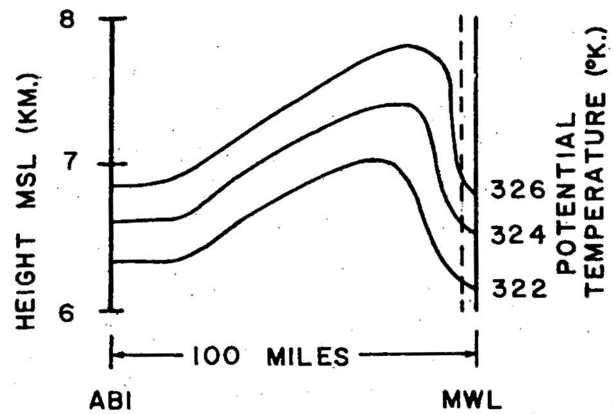
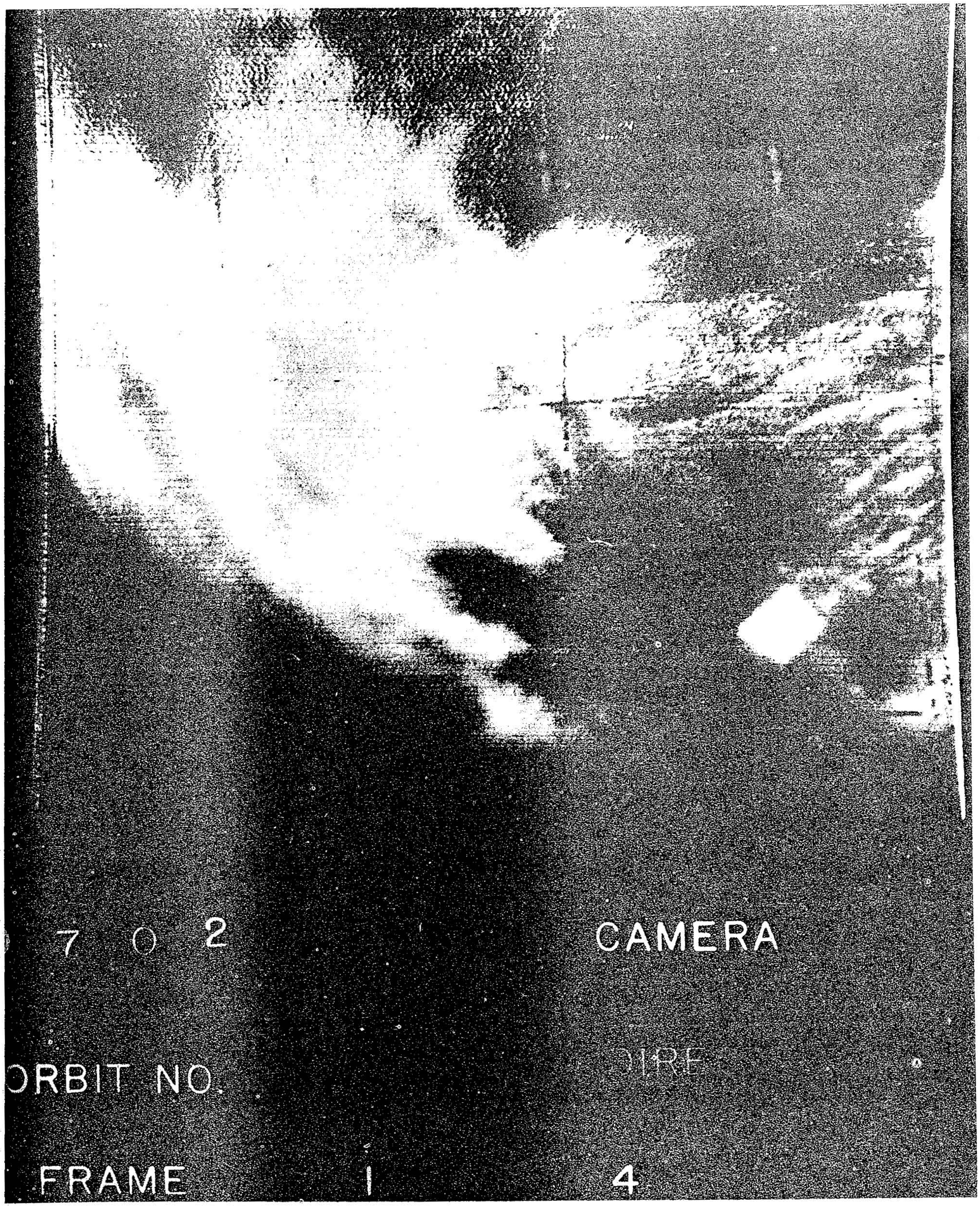


Figure 13.– Cross section of potential temperature through active squall line, utilizing traverse and aircraft sounding data.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The WADD-NASA portion of the 1960 season produced a number of scientific "firsts", namely: [24].

1. A scientific collection of turbulence data at high altitudes in thunderstorms.
2. Deliberate penetration flights by instrumented aircraft, including delta-winged type, through severe thunderstorms in squall lines which developed tornadoes and hail.
3. Deliberate supersonic penetrations through thunderstorms.

Case studies are in progress utilizing the 1960 data. One study was conducted by Whitney and Fritz [43] on the "square cloud" observed by TIROS I meteorological satellite. The "square cloud" (fig. 14) when rectified became an isolated, bright rhombic-shaped cloud mass located in southwestern Oklahoma. Indications were that the cloud was associated with convective activity that was studied by the NSLSRP aircraft and penetrated one-half hour before satellite picture time. The dew-point front appeared as a distinct boundary separating cloud areas and clear sky.

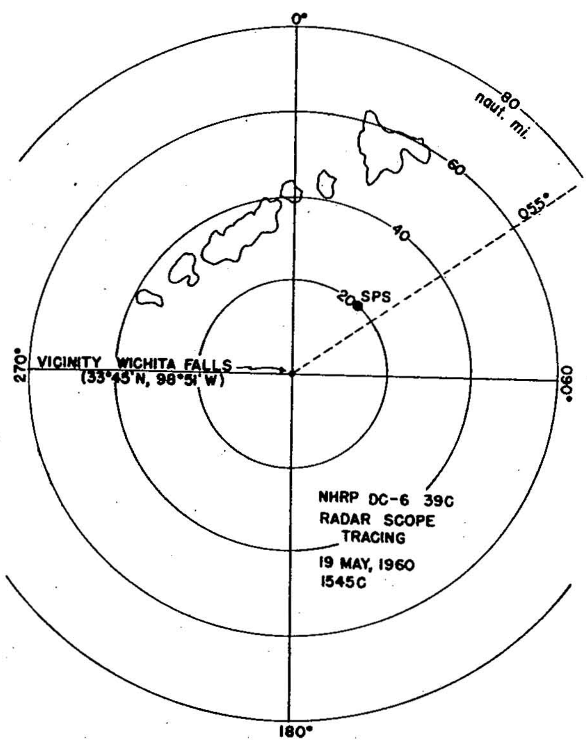

Figure 15.- Tracing from DC-6 radar.

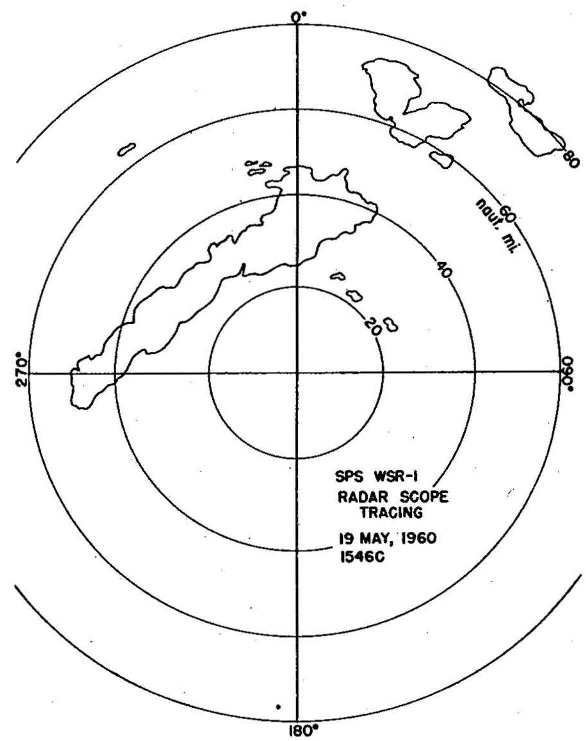

Figure 16.- Tracing from Wichita Falls radar.

Other studies using radar data (figs. 15, 16), turbulence data (figs. 17, 18), aircraft data similar to that obtained in previous years, rawinsonde and surface network data (fig. 19) are now being conducted. Some 1960 preliminary findings are:

1. Liquid water was frequently found in clouds near the 40,000-foot level, when tops of the thunderstorms were above that level. The environment temperatures from rawinsondes were near -45°C.

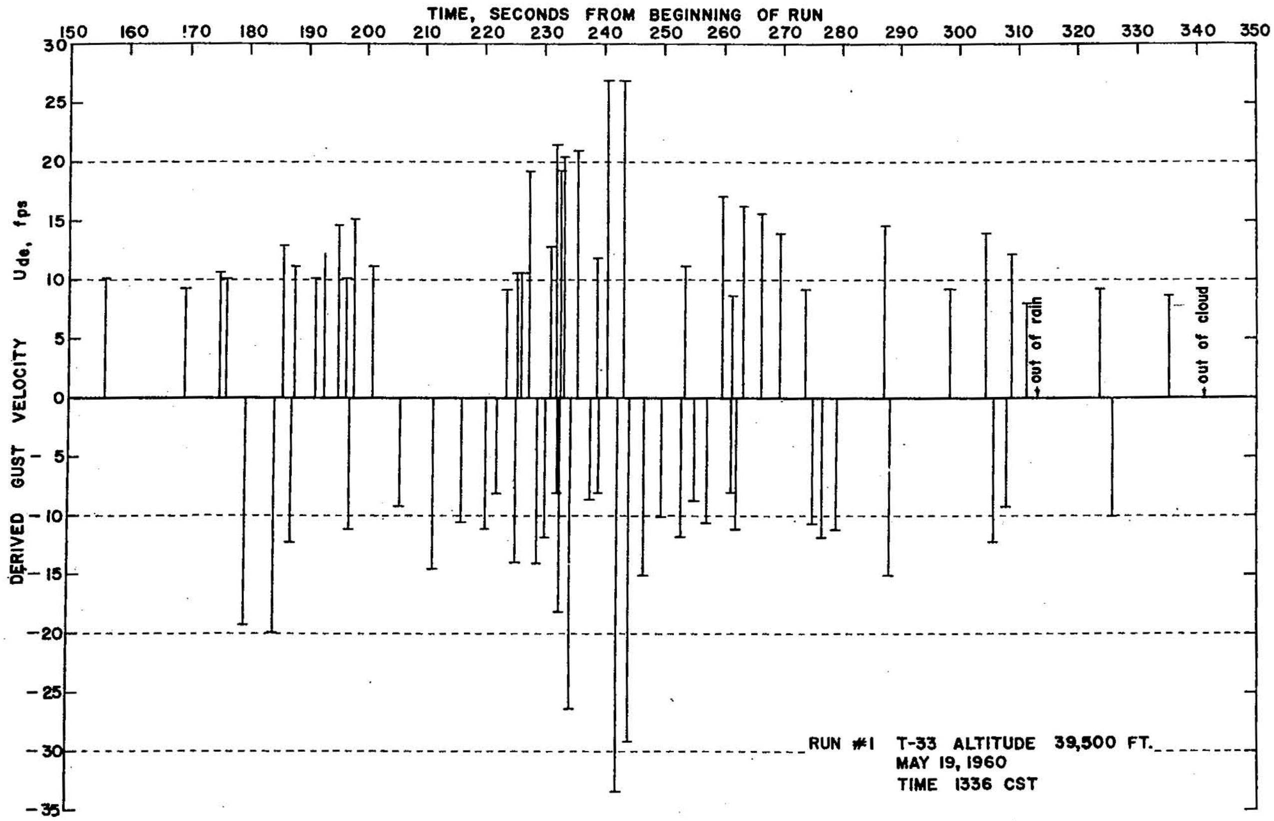

Figure 17. –Bar graph of derived gust velocities from a thunderstorm penetration. (Reproduced by courtesy of NASA.)

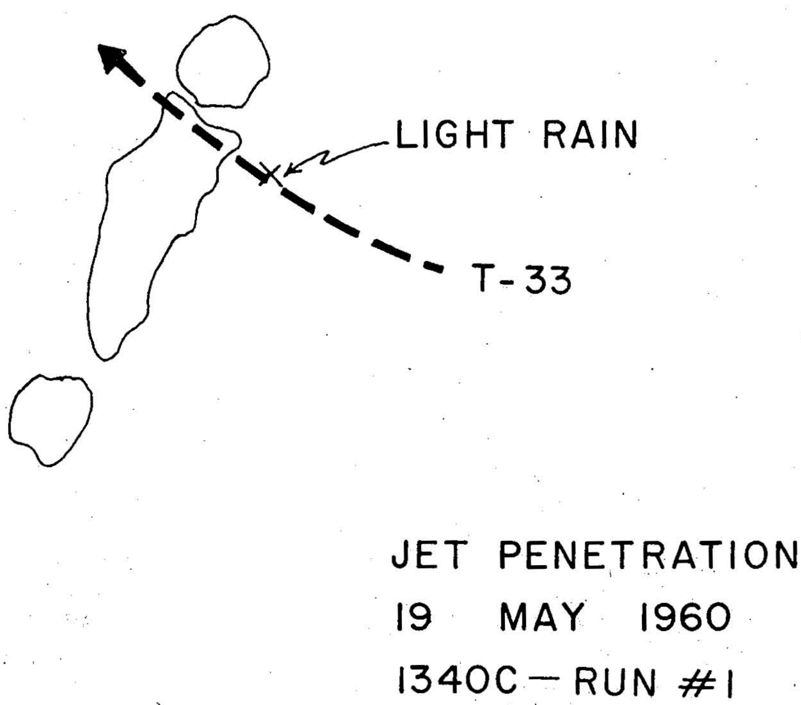

Figure 18. –Flight path of T-33 aircraft shown with respect to radar echoes. (Corresponding to data in figure 17.)

2. Large hail was occasionally encountered in thunderstorm tops as high as 40,000 feet, but more often at 30,000 feet.
3. Generally, turbulence was reported to be more severe in the darkest visual portion of the thunderstorm.
4. From a first look at the turbulence data (fig. 17) and power spectrum analyses of it, isotropic turbulence was found in portions of the thunderstorm cloud.
5. Thunderstorm penetration at high altitudes by the T-33, F-102, and F-106 can be made safely if proper piloting techniques are followed. Continuous ignition is an adequate protection against F-102 flame-outs during thunderstorm penetrations.

The analyses of the turbulence data are forthcoming in the NSSP preprint series, written by NASA and Aeronautical Systems Division (forerly WADD).

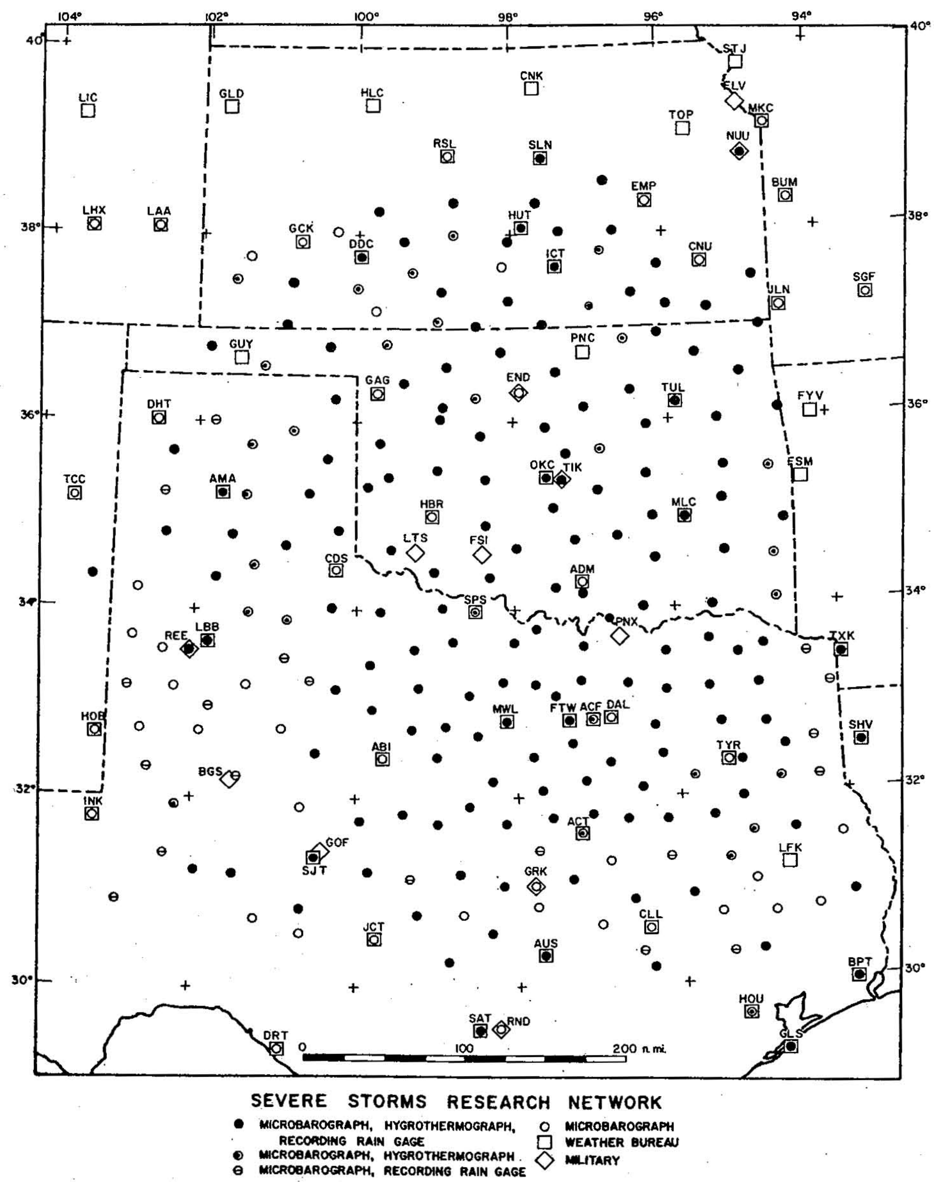

Figure 19. –Severe Storms Research Network.

A large contribution of TRAP was in the field of planning. The experiences gained from the flight planning, operation, and data reduction of a single aircraft operation proved invaluable and contributed heavily to the success of the first NSLSRP multi-aircraft operation. Likewise, the 1960 season provided ample examples of problems involved in operating a multi-aircraft project. The usage of the data has brought to light needs and deficiencies, such as the lack of air-borne wind measuring equipment, which have pointed out corrective measures for the future.

A factor which contributed greatly to the project's success was the interest of the pilot, Jim Cook, in his work. In addition to the many duties of flying the aircraft, he added the meteorological duties of obtaining soundings at fixed points, assuring proper functioning of instruments and recorders, and recording times, locations and observations on tape. It is indeed remarkable that there were only a few flights which did not include complete recorded data from all instruments.

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APPENDIX

Research Reports by TRAP and NSLSRP Personnel

Listed below are papers on the general subject of severe convective storms, prepared by personnel associated with the Tornado Research Airplane Project and the National Severe Local Storms Research Project, through the 1960 operative season. As noted in the text, the Severe Local Storms Forecast Center (SELS) for a time had the responsibility of running the aircraft investigations, and no distinction is made as to authorship by people of one group or the other. This listing does not, however, include all papers written by SELS personnel during the period covered.

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