INSTITUTES FOR ENVIRONMENTAL RESEARCH
National Severe Storms Laboratory
Norman, Oklahoma
April, 1967

Thunderstorm Circulations and Turbulence Studies from Aircraft and Radar Data

JAMES C. FANKHAUSER

J. T. LEE

Technical Memorandum IERTM-NSSL 32

U.S. DEPARTMENT OF COMMERCE / ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

INSTITUTES FOR ENVIRONMENTAL RESEARCH

NATIONAL SEVERE STORMS LABORATORY TECHNICAL MEMORANDA

The National Severe Storms Laboratory, Norman, Oklahoma, in cooperation with other government groups, and with units of commerce and education, seeks to increase understanding of severe local storms, to improve methods for detecting these storms and for measuring associated meteorological parameters, and to promote the development and applications of weather radar.

Reports by the cooperating groups are printed as NSSL Technical Memoranda, a sub-series of the ESSA Technical Memorandum series, to facilitate prompt communication of information to vitally interested parties and to elicit their constructive comments. These Memoranda are not formal scientific publications.

The NSSL Technical Memoranda, beginning with No. 28, continue the sequence established by the U.S. Weather Bureau National Severe Storms Project, Kansas City, Missouri. Numbers 1-22 were designated NSSP Reports. Numbers 23-27 were NSSL Reports, and 24-27 appeared as a subseries of Weather Bureau Technical Notes.

Reports in this series are available from the Clearinghouse for Federal Scientific and Technical Information, U.S.Department of Commerce, Sills Bldg., Port Royal Road, Springfield, Virginia 22151.

FOREWORD

The studies presented here have been made possible through the cooperation and substantial support of the Aeronautical Systems Division, U. S. Air Force; the Federal Aviation Agency; the U. S. Navy; and the Research Flight Facility, Institute for Atmospheric Sciences, ESSA.

TABLE OF CONTENTS

ASSOCIATION BETWEEN ATMOSPHERIC TURBULENCE AND RADAR ECHOES IN OKLAHOMA

J. T. Lee
National Severe Storms Laboratory

ABSTRACT

Turbulence experienced by aircraft during penetration of Oklahoma thunderstorms is compared with the characteristics of associated radar echoes. The correlation coefficient between the standard deviation of the derived gust velocity and the maximum radar reflectivity of the penetrated storm is about .55, according to data collected during 87 storm flights made by a USAF F-100 aircraft during 1964 and 1965. The correlation between the standard deviation and radar reflectivity gradient is less than 0.3. Other characteristics of the radar echo such as maximum reflectivity gradient, maximum reflectivity along flight path, and average gradient of reflectivity along the flight path are investigated, but are not found to contribute appreciably to the estimation of turbulence. At present, the maximum radar reflectivity of a storm seems to be the best indicator of turbulence encountered by an aircraft. The data show a lower frequency of severe turbulence at 37,000 feet altitude than at 27,000 feet, though the incidence of weaker categories is about the same.

1. INTRODUCTION

The Federal Aviation Agency, National Aeronautics and Space Administration, British Royal Aircraft Establishment, Air Force Aeronautical Systems Division (ASD), U.S. Navy, and National Severe Storms Laboratory (NSSL) have pooled personnel, aircraft, and funds to study turbulence in and near convective clouds. This report is based on data obtained from 87 penetrations made by ASD F-100F aircraft in 1964 and 1965 and 40 penetrations by an F-11 aircraft in 1964.

An objective of the program is to associate radar echo characteristics with turbulence in and near convective clouds. The main guide lines in the penetration program have been stated before [1] but are reiterated as follows:

1. Sampling was confined to one flight level.

2. Thunderstorms were within optimum radar range; i.e., 20 to 100 n.mi. radius of Norman.

3. *Reflectivity* factors (Z_e) in the storm were not to exceed $10^5 mm^6/m^3$.

4. Thunderstorms satisfying (2) and (3) above were sampled on a random basis.

2. DATA ACQUISITION

The radar observations were coordinated in time and space with aircraft flight paths, by referencing aircraft and radar operations to the same master clock. The primary radar was the WSR-57 located in Norman, Oklahoma, equipped with both a step-attenuation program and a contoured echo intensity presentation (Figure 1) [2]. Radar data processing has been discussed by Gray and Wilk [3]. The radar reflectivity (Z_e) used in this paper has been discussed by Battan [4] and by Wilk and Kulshrestha [5].

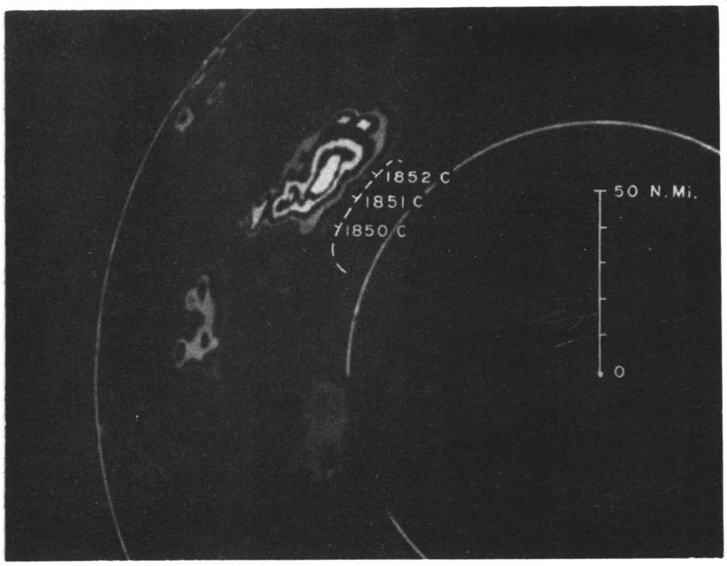

Fig. 1 - Integrated log-contour radar scope display at 1851 C, May 25, 1965. Corresponding aircraft track is superimposed and is shown as a dashed line.

F-100 instrumentation included gust vanes, accelerometers, rate gyros, free air temperature sensor (Rosemount type), pressure, and other sensing equipment described by Miller [6]. The F-11 data was obtained with a VGH (Velocity-Gust-Height) recorder and a photographed instrument panel. In 1965, F-100 rudder and elevator positions were also recorded, to help evaluate the gust measuring equipment and determine pilot inputs which tend to mask the turbulence data. Derived gust velocities (U_{de}) were computed following the method of Pratt [7]. Maximum values and standard deviations of U_{de} were used as turbulence indicators. Aircraft data were correlated with various radar echo characteristics as detailed in a previous paper [1].

Flight operations were conducted during April, May, and early June with the greatest activity occurring during the month of May.

3. DATA ANALYSIS

Flight data were obtained primarily near 27,000-ft. pressure altitude in 1964. In 1965 the principal sampling altitude was 37,000 ft., not far below the ceiling of commercial jet operations. In 1964 nearly all flights passed through storm centers, while the 1965 flights were designed to pass through the edges of large storms -- sometimes missing the centers by as much as 15 n. mi.

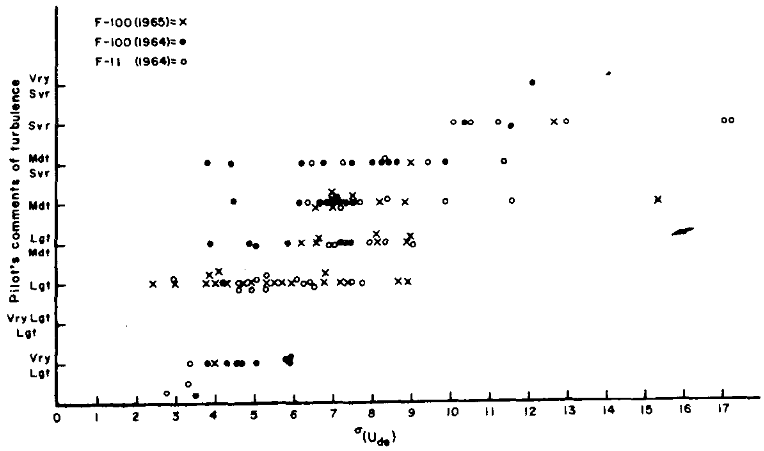

Fig. 2 - Pilots' evaluation of turbulence compared to computed standard deviation of derived gust velocities.

Figure 2 compares the pilots' characterization of turbulence during particular flights with corresponding standard deviations of derived gust velocities $\sigma(U_{de})$. Although the pilot and instrument evaluations generally agree, only $(U_{de})_{max}$ and $\sigma(U_{de})$ are used in the radar echo-turbulence comparison. Table 1 relates values of U_{de} and $\sigma(U_{de})$ to various turbulence categories.

Table 1. Turbulence Categories

Turbulence Category	U_{de} Values (fps)	$\sigma(U_{de})$ (fps)
Light	Less than 20	0 - 6
Moderate	20 - 34	6 - 8
Severe	35 - 50	8 - 15
Extreme	Above 50	Above 15

Because Lappe's analysis [8] of 1965 test flights shows that a 0.5 degree change in elevator position can produce a 0.1 g change in the recorded acceleration, all portions of the 1965 flights exhibiting large pilot input (0.5 degree elevator movement) were removed from the data sample. Radar data used are similar to the digitized format discussed by Kessler and Russo [9]; and all analyses are based on square grid spacings of 2.5 n. mi.

Figure 3 compares $\sigma(U_{de})$ and the maximum radar echo intensity (maximum storm reflectivity factor, Z_e) of cells recorded during aircraft penetrations. Figure 4 shows $(U_{de})_{max}$ for each penetration with the corresponding $(Z_e)_{max}$ of the cell under observation. The similarity between the two graphs is supported by consideration of Figure 5, which shows a linear relationship between $(U_{de})_{max}$ and $\sigma(U_{de})$ during 1965. (The correlation coefficient $r = 0.89$.)

Since the standard deviation is not greatly influenced by extremes, the correlation coefficients involving $\sigma(U_{de})$ are higher than those with $(U_{de})_{max}$.

The distributions of $\sigma(U_{de})$ against

(a) $Z_{e(max)}$ along the flight path,

(b) maximum reflectivity gradient ($dZ_e/dx_{\ max}$) along the flight path, and

(c) average reflectivity gradient $\overline{(dZ_e/dx)}$ along the flight path

are shown in Figures 6, 7, and 8, respectively. Table 2 lists corresponding correlation coefficients for 1964 and 1965 data.

The storms investigated in 1964 and 1965 were approximately the same size, and it seems that the lower correlation coefficient between turbulence and reflectivity gradient in 1965 may be related to the larger percentage of 1965 flights conducted far from the core of maximum radar reflectivity. Probably the higher 1964 correlation reflects principally the tendency for $Z_{e(max)}$ and its gradient to be more positively correlated when the latter is calculated along a path through the storm core.

Combinations of maximum reflectivity gradient to indicate turbulence have been discussed previously [1], and data obtained in 1965 (Table 2) reinforce earlier indications that the parameters in combination are little better than the reflectivity taken alone.

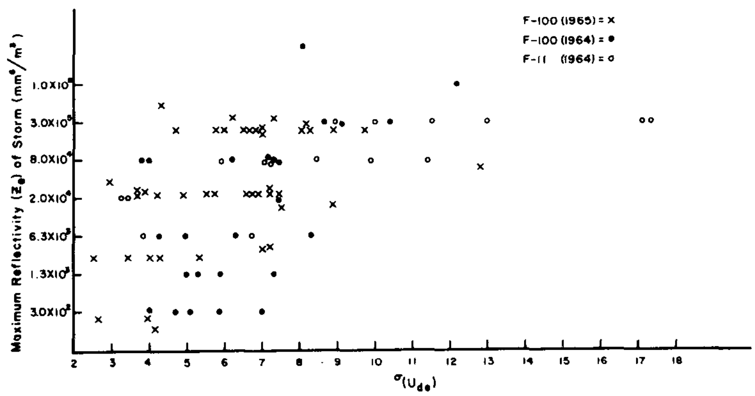

Fig. 3 - Standard deviation of derived gust velocities of each penetration compared to the maximum radar reflectivity.

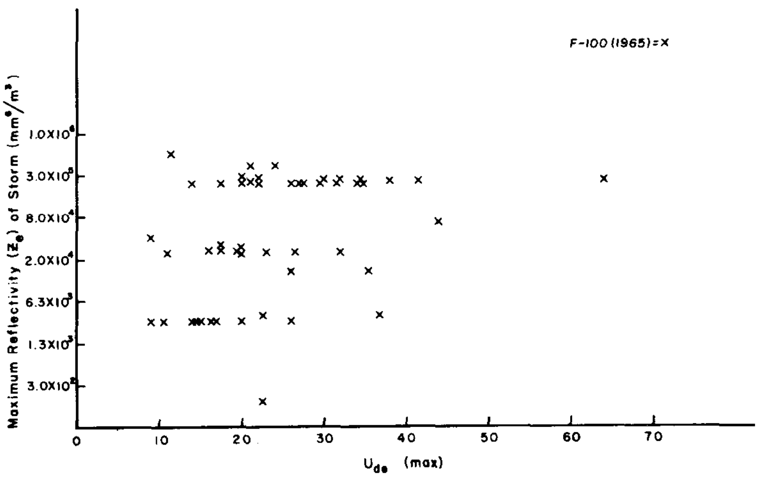

Fig. 4 - Maximum derived gust velocity related to maximum radar reflectivity.

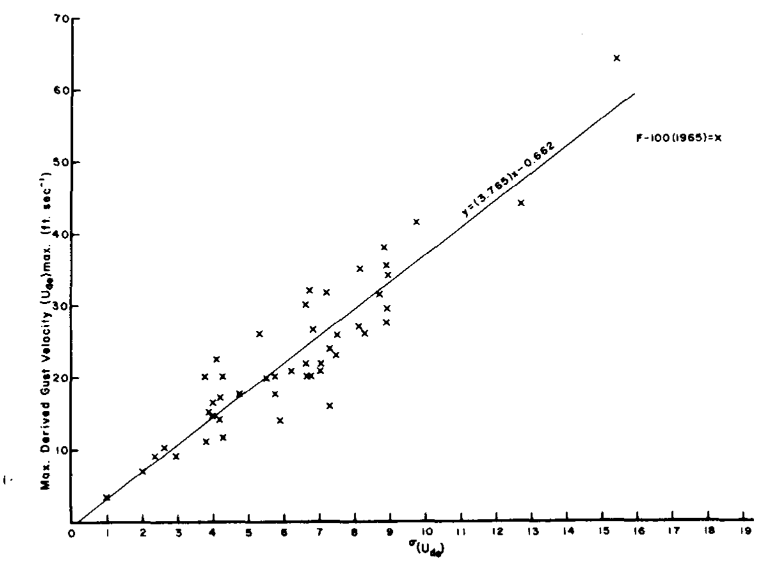

Fig. 5 - Comparison of the 1965 standard deviation of the derived gust velocities and the maximum derived gust velocities for each penetration.

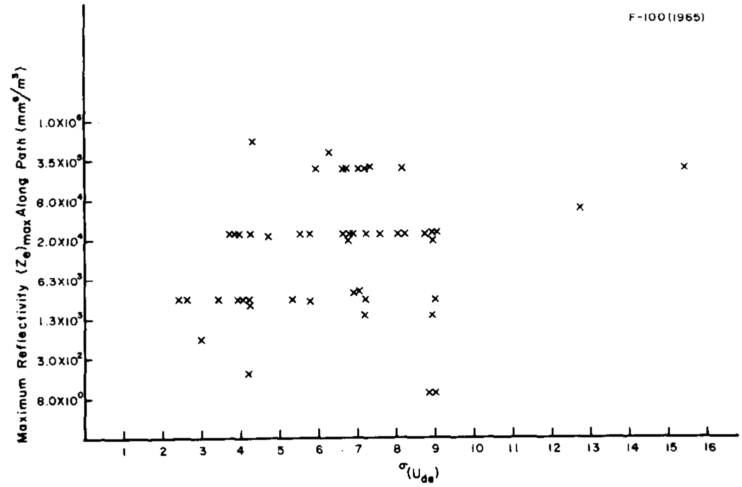

Fig. 6 - The maximum radar reflectivity along the flight path compared to the standard deviation of the derived gust velocities.

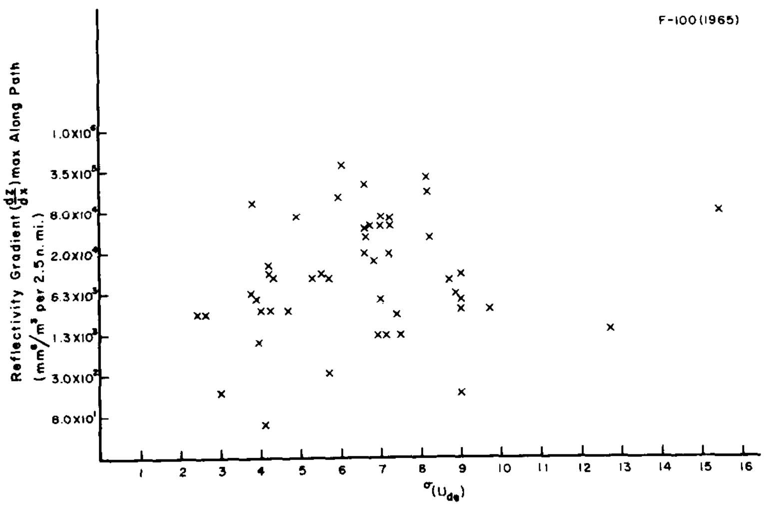

Fig. 7 - Maximum gradient of the radar reflectivity along the flight path compared to the standard deviation of the derived gust velocities.

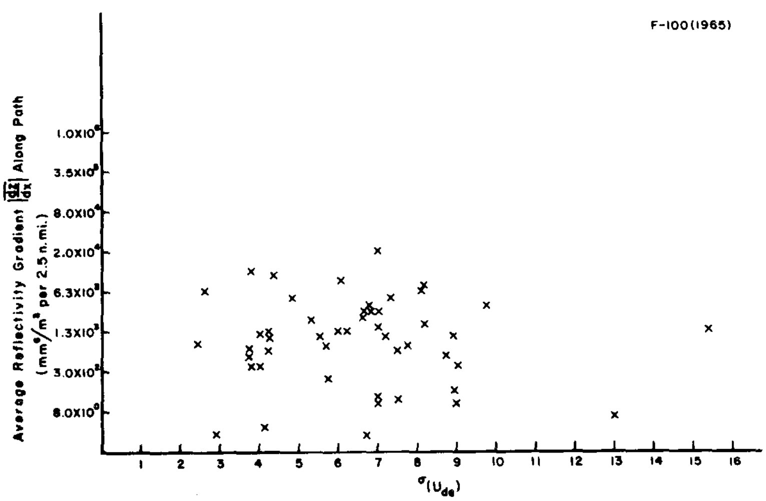

Fig. 8 - Average gradient of the radar reflectivity along the flight path compared to the standard deviation of the derived gust velocities of each penetration.

Table 2. Linear Correlation Coefficient for Turbulence and Radar Echo Characteristics

Turbulence Measurement	Echo Characteristic	Correlation Coefficient 1964	Correlation Coefficient 1965
$\sigma(U_{de})$	$Z_{e(max)}$ (of storm)	0.514	0.516
$\sigma(U_{de})$	$Z_{e(max)}$ (of storm)		0.220
$\sigma(U_{de})$	Z_e gradient$_{(max)}$ (along flight path)	0.322	0.194
$\sigma(U_{de})$	Z_e gradient$_{(ave)}$ (along flight path)	0.315	- 0.092
$U_{de(max)}$	$Z_{e(max)}$ (of storm)	0.464	0.329
$U_{de(max)}$	$Z_{e(max)}$ (along flight path)		0.068
$U_{de(max)}$	Z_e gradient$_{(max)}$ (along flight path)	0.302	0.091
$U_{de(max)}$	Z_e gradient$_{(ave)}$ (along flight path)	0.241	0.226

Severe turbulence encounters outside the core areas were as frequent in 1965 as in 1964. This sustains the earlier concept [1] that severe turbulence is widely distributed in storms whenever the core Z_e indicates damaging hail ($Z_e = 10^5/mm^6/m^3$). Figure 1 shows a flight on May 25, 1965. The main core of the storm with $Z_e = 2.5 \times 10^5 mm^6/m^3$ was 12 n. mi. west of the flight path. For this flight (U_{de}) max is 34 ft. per sec. and $\sigma(U_{de})$ is 8.97. The British Scimitar aircraft flying the same pattern on this occasion experienced similar turbulence.

Figures 9 and 10 show the distributions of derived gust velocity recorded during the 1964 and 1965 seasons. The data indicate lower frequency of extreme turbulence at the higher altitude. The frequency of moderate turbulence (U_{de} 35 ft. per sec.) is about the same at 27,000 and 37,000 ft.

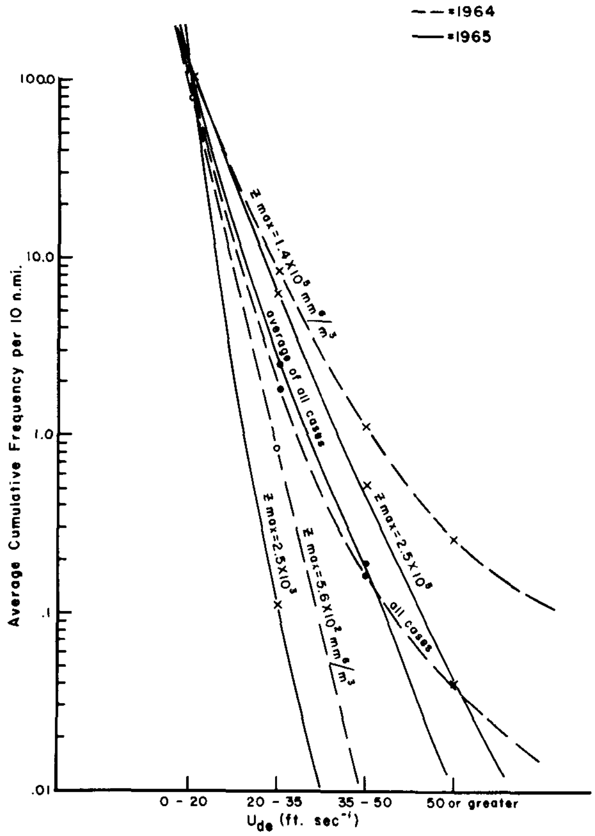

Fig. 9 - Average cumulative frequency of derived gust velocities per 10 n. mi. of flight in thunderstorms for representative values of maximum radar reflectivities (Z_e) of storm cores.

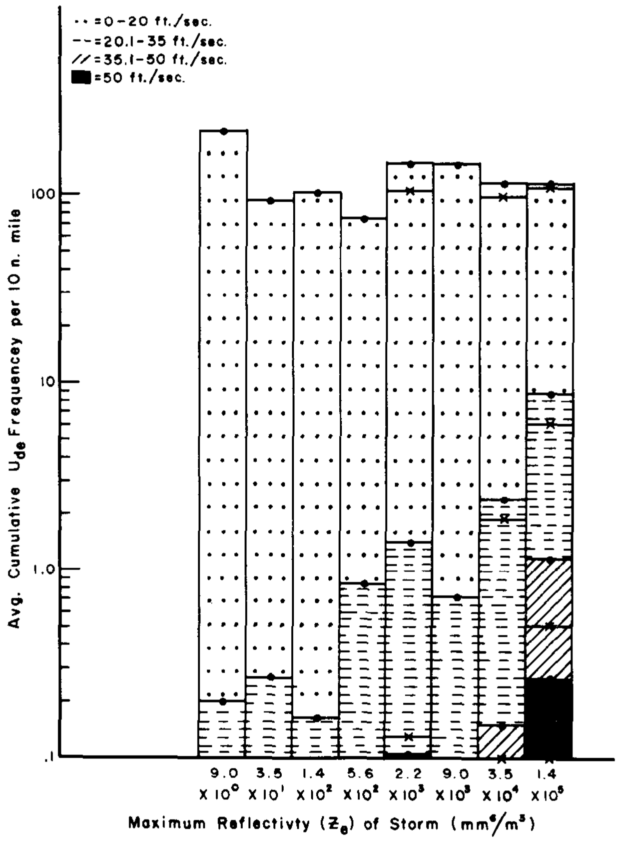

Fig. 10 - Average distribution of derived gust velocities per 10 n. mi. of flight in thunderstorms for 1964 and 1965.

4. SUMMARY

The 1965 data support the conclusions of earlier studies. The maximum reflectivity (Z_e) of the storm is the most reliable indicator of turbulence in thunderstorms. Moderate to severe turbulence may be encountered 10 to 15 miles from the center of storms whenever the maximum reflectivity is $3.5 \times 10^4 mm^6/m^3$ or more. The frequency of severe and extreme turbulence seems slightly diminished at higher altitudes.

REFERENCES

1. Lee, J. T., "Thunderstorm Turbulence and Radar Echoes 1964 Data Studies," ESSA Technical Note 3; NSSL Report 24, 1965, pp. 9-28.

2. Lhermitte, R. M. and E. Kessler, "A Weather Radar Signal Integrator," NSSL Tech. Memo No. 2, 1965, 8 pp.

3. Gray, K. C. and K. E. Wilk, "Data Processing at NSSL in 1964," ESSA Technical Note 3, NSSL Report 24, 1965, pp. 111-121.

4. Battan, L. J., Radar Meteorology, University of Chicago Press, 1959, 161 pp.

5. Wilk, K. E. and S. M. Kulshrestha, "Wave Length Dependence of the Radar Reflectivity of Water and Ice Spheres," ESSA Technical Note 3; NSSL Report 24, 1965, pp. 33-34.

6. Miller, E., "1964 Rough Rider Summary of Parameters Recorded, Test Instrumentation, Flight Operation and Aircraft Damage," Aeronautical Systems Division Technical Report ASD-TR-65-1, 1965, 40 pp.

7. Pratt, K. G. and W. G. Walker, "A Revised Gust-Load Formula and a Re-evaluation of V-G Data Taken on Civil Transport Airplanes from 1933 to 1950," National Advisory Committee of Aeronautics Report No. 1206, 1954, pp. 1-4.

8. Lappe, O., "A Preliminary Evaluation of the F-100 Rough Riders Turbulence Measurement System," Final Report on ESSA Contract W66-170, 1966 (to be printed in NSSL report series).

9. Kessler, E., and J. A. Russo, Jr., "Statistical Properties of Radar Echoes," in Proceedings 10th Weather Radar Conf., Wash., D. C., 1963, pp. 25-33.

SOME PHYSICAL AND DYNAMICAL ASPECTS OF A SEVERE RIGHT-MOVING CUMULONIMBUS

James C. Fankhauser
National Severe Storms Laboratory

ABSTRACT

The morphology and dynamics of an isolated severe thunderstorm are analyzed and interpreted using observations obtained by instrumented aircraft and radar. Several aspects of the Severe-Right (SR) quasi-steady-state thunderstorm model proposed by Browning are supported by features of the storm's motion pattern, RHI radar profiles, and by certain kinematic properties. Net cyclonic circulation measured near the cloud base is considered as a mechanism for steering the storm. Comparison of rainfall with low-level moisture convergence reveals that about 60% of the intercepted water vapor is deposited on the ground during the storm's persistent phase.

1. INTRODUCTION

Soundings by aircraft of convective storm environments have contributed fundamentally to our knowledge of storm dynamics (see Byers and Braham [4], Staff members, NSSP [15]). However, the full character of physical processes near and within cumulonimbus clouds is not well-known, and careful observations are still greatly needed. This paper presents an analysis of data collected near an isolated Cb on June 1, 1965, by two DC-6 aircraft operated as part of the NSSL observational program. During the aircraft investigations the radar precipitation echoes were constantly monitored by the NSSL WSR-57 radar.

2. SYNOPTIC SITUATION, CLOUD FEATURES, AND STORM MORPHOLOGY

Convergence along the dry front shown in figure 1(a) was enhanced by the orographic lift given to the moist air by the "Cap Rock" escarpment in the Texas panhandle (see topographic contours in figure 3).[1] These effects apparently combined to produce an initial precipitation echo on the NSSL WSR-57 radar at 1340 CST. During the following 30 minutes a thunderstorm grew as shown by photographs in figure 2. These photographs were taken from one of the investigating aircraft flying on a heading of 270° toward the southwest sector of the storm and they indicate the well-organized nature of the visual cloud. The storm system developed in a wind regime with typically pronounced vertical shear, and persisted nearly 5 hours. Its

[1] A vertical wind component of nearly 10 cm sec^{-1} is associated with horizontal winds of 10 m sec^{-1} lifted by an incline of 1000 ft. in 20 n. mi.

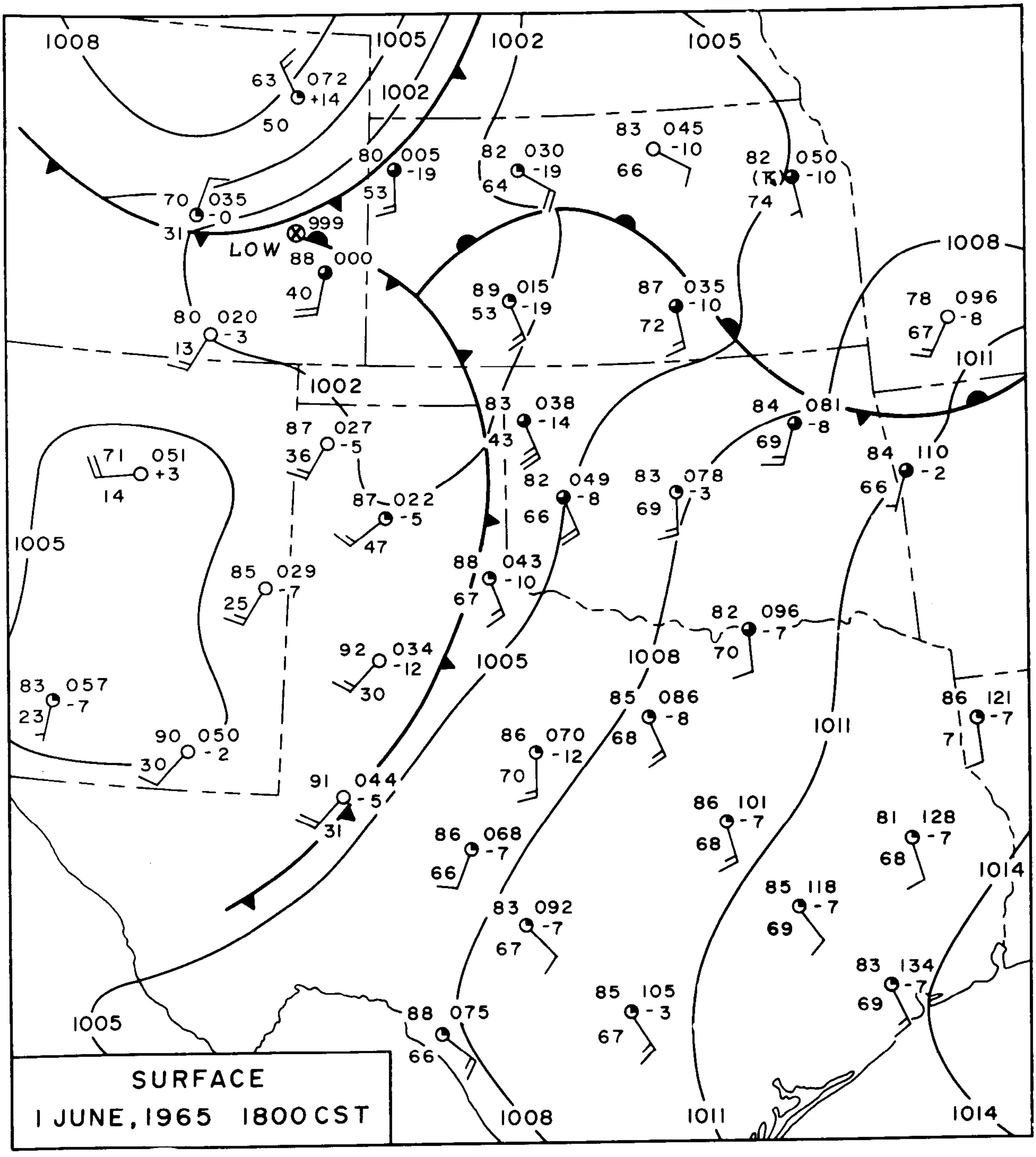

Figure 1a. Surface analysis, 1800 CST, June 1, 1965.

trajectory and evolution as a radar echo is shown in figure 3. Heavy hail damage was reported along much of the east-west portion of the track but no tornadic activity was observed.

Many features in the structure and behavior of this storm agree with the quasi-steady-state SR (Severe-Right) model of Browning [3]. The most prominent of these is the S-shaped track produced by the storm's rather sudden veering to the right during echo development and turning to the left shortly before dissipation. The hodographs shown in the inset of figure 3 illustrate that during much of the storm's lifetime it traveled to the right of the winds at all levels.

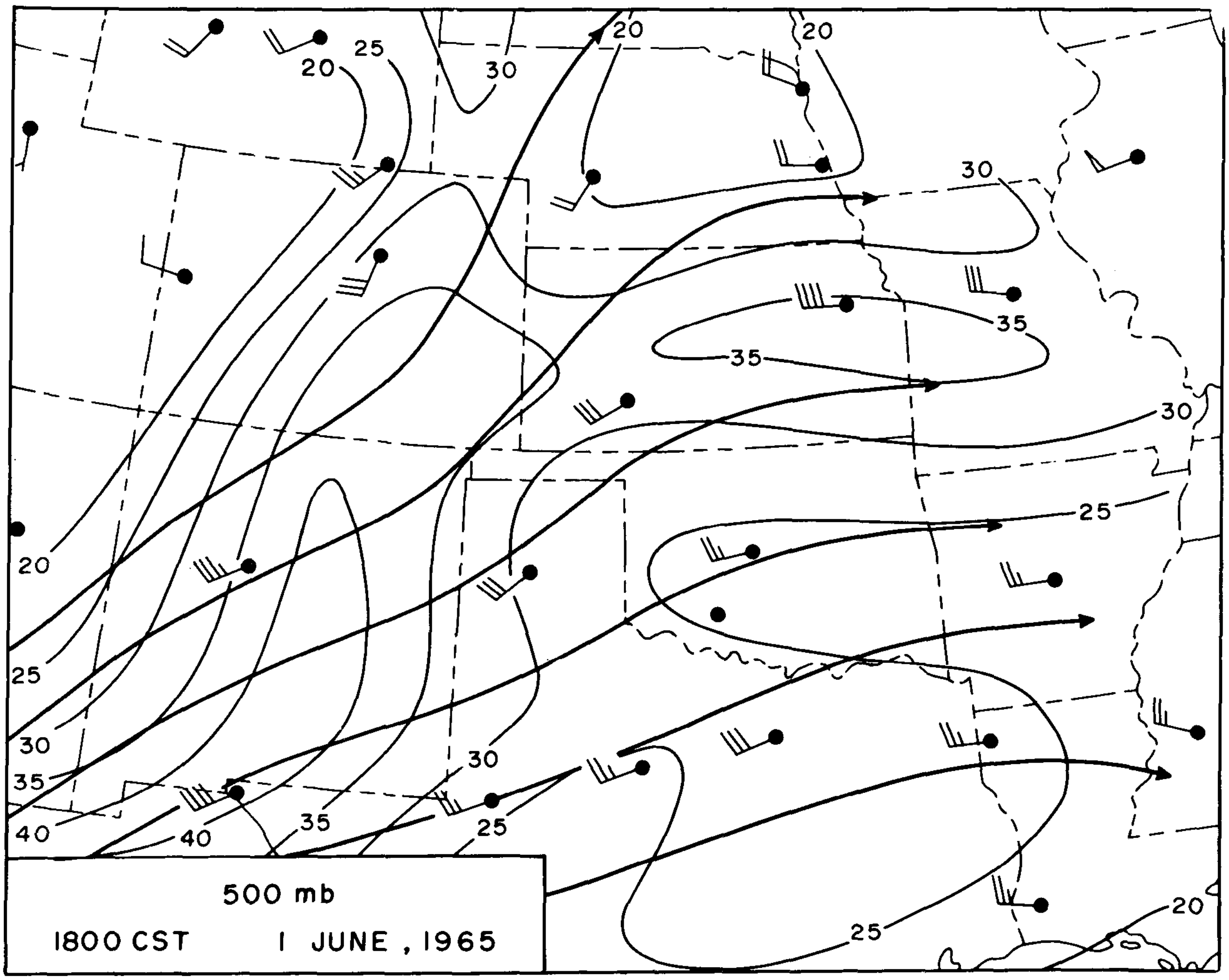

Figure 1b. 500-mb streamlines and isotachs in knots, 1800 CST, 1 June 1965.