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Further Studies of Thunderstorm Conditions Affecting Flight Operations: Turbulence

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The gust and draft data taken by the Thunderstorm Project in Florida and Ohio storms are analyzed and indicate the following: The level of the least turbulence between 4,000 and 26,000 ft altitude in a thunderstorm is at or near 4,000 ft which is ususally near the base of the cloud. The average thuderstorm in Ohio contains greater turbulence, in the levels flown by the project, than the average thunderstorm in Florida. The altitude displacements caused by thunderstorm drafts increase with height at least to a level 25,000 ft above the storm base. It is not likely that a thunderstorm draft will force a modern military or commercial airplane, if properly flown, dangerously close to level ground; However, the down-draft, even at low levelsmmay be dangerous for a light airplane with its low rate of climb and slow speed.

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Operating Problems (31)

Airplanes - Operation in thunderstorms (08476.4); Gusts - Effect on aircraft safety (47480.5); Turbulence, Atmospheric (95603); Thunderstorms - Characteristics (94145)

AIR WEATHER SERVICE
TECHNICAL REPORT 105-39

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# FURTHER STUDIES OF THUNDERSTORM CONDITIONS AFFECTING FLIGHT OPERATIONS: TURBULENCE

COELUM AD PROELIUM EULIGE

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HEADQUARTERS
AIR WEATHER SERVICE
WASHINGTON, D.C.

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Washington 25, D. C.

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Air Weather Service Technical Report 105-39, "Further Studies of Thunderstorm Conditions Affecting Flight Operations: Turbulence," is published for the information and guidance of all concerned. This report is the result of studies by Mr. Roscoe R. Braham, Jr., of the Weather Bureau-Air Force-Navy-NACA Thunderstorm Project, and Capt. Fred W. Pope, U.S.A.F., the Air Weather Service Liaison Officer to the Project. It may be considered as an extension of previous studies, "A Report on Thunderstorm Conditions Affecting Flight Operations," published as U. S. Weather Bureau Technical Paper No. 7, April 1948.

It is released with the concurrence of the Director, Thunderstorm Project, Hq., U. S. Air Force, and Hq., Air Materiel Command.

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## FURTHER STUDIES OF THUNDERSTORM CONDITIONS AFFECTING FLIGHT OPERATIONS: TURBULENCE

In routine flight operations it is not always possible to avoid thunderstorm flying. Although the trend is toward higher cruising levels, it is still impossible to top most thunderstorms and regardless of cruising altitude, it is necessary in take-offs and approaches to guide the aircraft through the low altitudes.

Although by flying above 15,000 feet the pilot can top the low cumulus and surrounding low clouds and see clear areas between the giant convective centers, it is often difficult for him to anticipate a course between thunderstorms without a sensing device such as radar. This points out the fact that thunderstorms will always be of major concern to the pilot and operations personnel and it is therefore necessary that they be aware of conditions likely to be encountered in flying through thunderstorms. In addition to the usual difficulties of cloud flying, thunderstorms present hazards due to lightning, turbulence and hail. Flight records show that turbulence is the most predominant hazard in thunderstorms and may be the principal cause of thunderstorm accidents. Its effects sometimes lead to loss of control or structural damage to the airplane. The studies reported herein are concerned with turbulence, including an analysis of the distribution of gusts and drafts in thunderstorms and their relation to other weather elements.

Gustiness of the surface winds and turbulence in the layer next to the ground have been studied for many years. The treatment has had to be statistical in nature because of the random character and high frequency of the turbulent eddies which make up the gustiness. The individual eddies or "turbulence elements" are small in size, are identifiable for only a short time and behave somewhat independently of surrounding elements. The gusts inside a thundercloud are of a similar nature and therefore are best treated statistically rather than individually.

Sustained updrafts and downdrafts, on the other hand, are large enough and last long enough to make it important to treat each draft as a unit, and to study the nature and life cycle of individual drafts as well as their effect on an airplane flying through them.

## Source of Data

The Thunderstorm Project* conducted its investigations during the spring and summer of 1946 in the vicinity of Orlando, Florida and during the spring and summer of 1947 in the vicinity of Wilmington, Ohio. The data used in the study presented here were obtained primarily from P-61C airplanes flying at 6,000, 11,000, 16,000, 21,000 and 26,000 feet MSL through Florida thunderstorms and at 5,000, 10,000, 15,000, 20,000 and 25,000 feet MSL through Ohio thunderstorms. These altitudes are

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*The Thunderstorm Project is a research group of the U. S. Air Force , U. S. Navy, National Advisory Committee for Aeronautics, U. S. Weather Bureau and several other contracting agencies under the direction of Dr. Horace R. Byers. The purpose of the Project is to study the structure and dynamics of the thunderstorm and for this purpose extensive measurements were made in thunderstorms during 1946 and 1947. Airplanes, radar, surface network stations, and balloon-borne instruments were used in gathering the data. Details of instrumentation and techniques of taking observations can be found in earlier reports of the Project. (Ref. 12, 13, 14 and 15).

approximately the height above the ground in Florida but in Ohio the ground is about 1,000 feet above sea level. In all, a total of 1363 penetrations were made through storms of Florida and Ohio. Storms were selected for investigation on the basis of their radar echo and visual appearance and no attempt was made to avoid those that looked too severe. The storm intensity, as reported by the Project pilots, ranged from light to very severe and should constitute a fair sample of typical Florida and Ohio thunderstorms.* No tornado funnels were observed under any of the clouds flown, although on May 13, 1947 a funnel from an adjacent cloud was observed shortly after the mission had been completed. Gusts and drafts encountered were computed from records obtained from equipment installed by NACA† and from photographs of a special panel of flight instruments. Correlated with these data are reports of the precipitation and turbulence intensities as recorded by the flight crews.

Thunderstorm Turbulence

The thunderstorm cell is characterized by a region of somewhat chaotic motions which result in a general transport of air upward (updraft) throughout the early stages of development, and downward (downdraft) throughout the later stages, particularly where rain develops. If this velocity field is intersected by a co[illegible]entional-type airplane, two characteristic responses are observed. First, the airplane may be displaced in altitude because of the mean upward or downward motions and secondly, the airplane may be subjected to a series of sharp

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*The fact that gust velocities measured were considerably in excess of those expected on the basis of previous studies by the National Advisory Committee for Aeronautics also indicates that the sample obtained probably is not biased by weak storms. (Ref. 10).

†National Advisory Committee for Aeronautics.

accelerations without a systematic change in altitude. These accelerations are caused by abrupt changes in velocity of the drafts and by small vortices or whirling masses of air. All such discontinuities in the velocity field are called gusts. Many of the larger gusts are thought to represent abrupt changes in draft speed, but the vast majority of them are best described as small vortices. Such vortices are usually embedded in a draft but may be in areas where no drafts are measured.* It is thought that drafts provide the primary driving mechanism of the vortices. In this connection, the larger gusts are invariably associated with strong drafts.

The nature of this type of atmospheric gustiness has been investigated by engineers of the Gust Loads Section of NACA who devised and carried out the program of gust measurements for the Thunderstorm Project. Earlier studies by NACA (Ref. 11) have shown that although the accelerations caused by a gust may have components along the pitch, yaw or roll axis in any combination, measurements about a single axis provide adequate data for depicting the field of gustiness. Measurements by the Thunderstorm Project were made only along the vertical axis. The measured accelerations caused by the gusts are used in the sharp-edged gust formula for computing the effective velocity† of the gusts.

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*Gusts are not confined to thunderstorms alone. For instance, every pilot and weatherman is familiar with turbulence due to orographic effects, surface heating, etc. The Royal Aircraft Establishment has recently reported turbulence outside cumulus clouds in the atmosphere between 20,000 and 40,000 feet. (Ref. 6).

†The effective velocity is the vertical component of the actual velocity of a gust that would have produced the noted acceleration provided such gust satisfied the assumptions under which the sharp-edged gust formula was derived. (Ref. 9).

It is common practice among aeronautical engineers to use the effective gust velocity as a measure of the strength of the turbulence. Opinions have been expressed that the effective gust velocity combined with the gust frequency determines the intensity of the turbulence as reported by aircrews. Through comparisons of pilot reports of turbulence intensity with measured effective gust velocities and gust frequencies it has been shown* that if the largest gust in a group of several contiguous gusts exceeds about 15 fps and at the same time the gust frequency is greater than 8 per 3,000 feet of traverse, the Project aircrews reported the turbulence as "heavy". When the region under consideration is expanded to the length of one complete pass through a thunderstorm, heavy turbulence was reported for the traverse as a whole whenever the mean maximum effective gust velocity per 3,000 feet of traverse exceeded 8 fps and the frequency exceeded 4 per 3,000 feet of traverse.

It is therefore important to realize that highly experienced airmen will report heavy turbulence in areas where the gusts have velocities that at first might seem relatively small. The association of high-velocity gusts with areas of high gust frequency is shown in Figure 1, in which is plotted the effective velocity of the largest gust per 3,000-foot interval against the number of gusts within that interval. It is thus evident that whenever gusts with effective velocities greater than 8 fps are encountered it is quite probable that the frequency will exceed 4 per 3,000 feet with the result that the turbulence would be reported as heavy, even by pilots of wide experience.

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*Unpublished manuscripts of Capt. Fred W. Pope and Miss Mary E. Thomas.

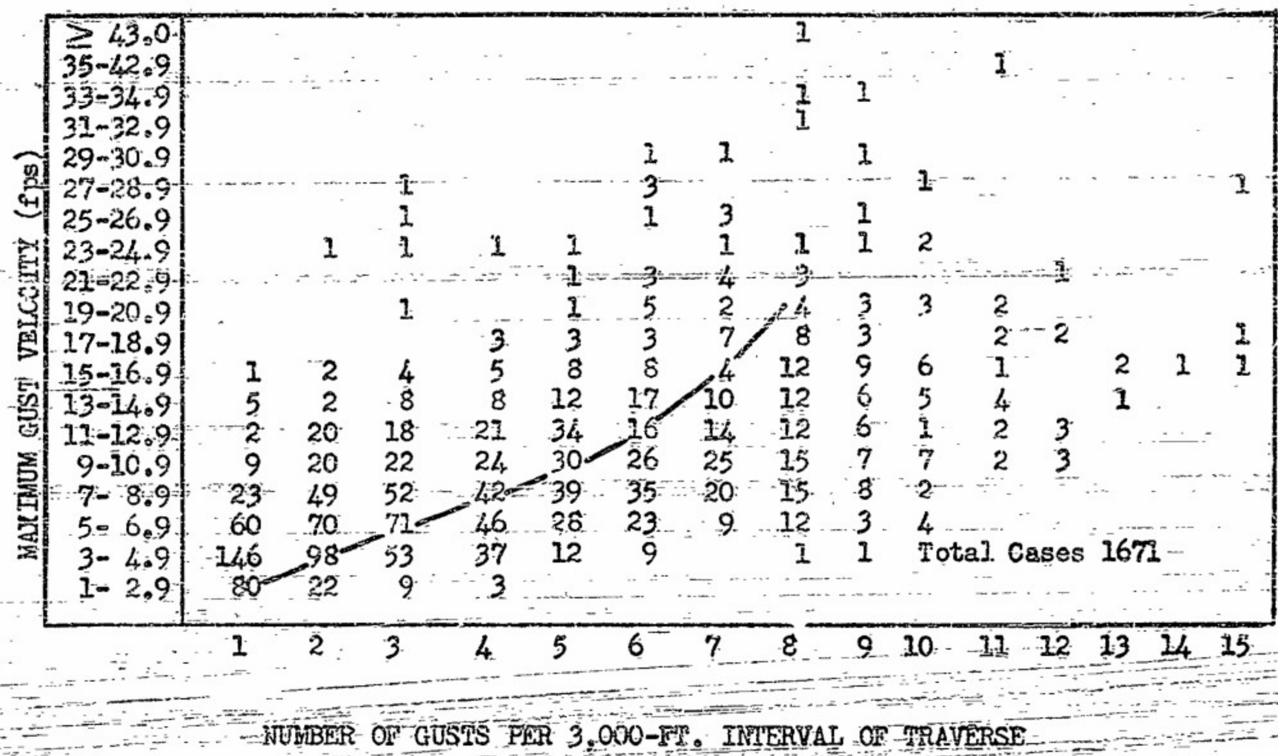


Fig. 1 -- Relationship between speed of maximum gust in a 3000-ft. interval of traverse and number of gusts in that interval. Curve represents the regression function of mean gust frequency on gust velocity. Correlation coefficient is 0.61. Based upon data from Florida and Ohio operations.

## Altitude Distribution of Turbulence

The pilot and operation personnel are interested in the probability of encountering strong gusts. The need is therefore apparent for information regarding the distance required to fly in thunderstorms to encounter a gust greater than a given value. Such information is contained in the turbulence measurements made by the Thunderstorm Project. The number of gusts encountered on each of the 1363 traverses through thunderstorms by Project airplanes was very large and to reduce the labor of evaluating the records, it was necessary to break the traverses into short intervals and treat each interval as a unit. For each 3,000-foot interval of each traverse for storms flown in

Florida and each 10-second interval of each traverse for storms flown in Ohio, the maximum positive and negative effective gust velocities, and the number of gusts encountered greater than a value of 2.0 fps were computed. The maximum effective gust velocities for each 3,000-foot or 10-second interval of traverse, regardless of sign, was used in determining the distribution of gusts with altitude.

As would be expected, at all altitudes flown, the low gust velocities occur more frequently than high gust velocities. This is true regardless of the altitude although the mean maximum gust velocity per 10 seconds of traverse is nearly the same at all altitudes. (Tables 1 and 2).* However, the altitude variation in the mean maximum gust velocity per unit distance is not of great importance to flying because it is the extreme gust velocities that contribute most to personal discomfort and to the stress on the airplane structure. In the data taken by the Thunderstorm Project there is a distinct altitude variation in the distribution of the higher-velocity gusts. Figures 2 and 3 graphically indicate the number of miles of flight

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*It should be pointed out that the data used for these two tables are somewhat different due to the use of different techniques in determining the in-cloud distances flown for the two seasons. For the Florida data there is no satisfactory method of separating the data measured in clear air near the thunderstorm from the data within the cloud. On the other hand, in the Ohio data these are easily separated. Table 1 for the Ohio data is based upon the data actually taken inside the visible cloud. Table 2 for the Florida data includes both in-cloud data and data taken near the thunderstorm. As a means of obtaining an estimate of the amount of Florida data that was taken in clear air, the visual cloud was compared with the radar echo for six selected Ohio storms in which there were 1380 miles of flight within the visual cloud. The amount of traverse inside the radar echo was compared with the amount outside the echo for sixteen selected Florida storms with a total of 2819 miles of flight data used. For the Ohio data, it was found that 35 per cent of the flight within the visual cloud is beyond the limits of the radar echo. Furthermore, approximately 20 per cent of the flight distance within the radar echo was not in thunderstorms at the various altitudes necessary to encounter an effective gust velocity greater than a given value. (Tables 3 and 4). It is important to notice that in both seasons' data there is a minimum of the higher velocity gusts at the lowest levels flown. The minimum frequency at the 25,000-foot level in Florida is less pronounced in the Ohio data.

The most evident feature in comparing the gust data for the two seasons is the fact that there were more high-velocity gusts per mile of flight in the Ohio storms than in the Florida storms. It was necessary to fly 133 miles in Florida thunderstorms to encounter a maximum gust of 24 fps as compared to 86 miles in Ohio. The most important features of the two figures, if they are significant, are the altitude variations in the gust velocities. It is possible that the variations that occur above the bulge near 16,000 feet in Florida and 10,000 feet in Ohio are a result of the sample, although a distance of over 12,000 miles of thunderstorm flight for the two seasons would usually not be considered a small sample. There is, however, other evidence that indicates that the minimum of turbulence found near the cloud base is significant.

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within the visual cloud. These conditions are brought about by the fact that the radar echo on the main control radar represents a horizontal projection of the entire radar echo, whereas the water content high enough to give detectable radar signals is confined to the main portion of the cloud that may be tilted from the vertical by a shear in the wind field. (Had an airborne radar giving a horizontal cut through the cloud for its particular flight level been used, it is not conceivable that there would have been portions of the radar echo outside the visual cloud). In the sixteen Florida storms, it was found that about 30 per cent of the total data were beyond the radar echo. If one assumes that the storms of the two localities are approximately alike in the manner in which they appear on the radar, it follows that most of the data taken in Florida is actually within the visual cloud and as a first approximation may be compared with the Ohio data which are known to be within the visible cloud.

Table 1--Frequency distribution of maximum effective gust velocity per 10-second interval of traverse at various altitudes. Based upon P-61C flights through Ohio thunderstorms, 1947.

| Maximum effective gust velocity (fps) | Flight Altitude (ft-msl) | | | | | Total |
|---|---|---|---|---|---|---|
| | 5,000 | 10,000 | 15,000 | 20,000 | 25,000 | |
| 0- 4 | 736 | 1053 | 1219 | 812 | 622 | 4442 |
| 4- 8 | 470 | 798 | 850 | 527 | 285 | 2930 |
| 8-12 | 231 | 474 | 527 | 345 | 200 | 1777 |
| 12-16 | 88 | 234 | 226 | 168 | 92 | 809 |
| 16-20 | 22 | 88 | 95 | 63 | 38 | 306 |
| 20-24 | 7 | 37 | 36 | 24 | 14 | 118 |
| 24-28 | 5 | 5 | 12 | 6 | 12 | 40 |
| 28-32 | 0 | 5 | 6 | 2 | 2 | 15 |
| 32-36 | 0 | 2 | 2 | 2 | 1 | 7 |
| 36-40 | 0 | 0 | 2 | 1 | 0 | 3 |
| 40-44 | 0 | 0 | 1 | 0 | 0 | 1 |
| Total Number | 1559 | 2695 | 2976 | 1949 | 1266 | 10,446 |
| Total Miles Flown | 791.8 | 1350.8 | 1579.5 | 1178.6 | 776.6 | 5677.2 |
| Mean of maximum gust velocity above 4 fps | 8.6 | 9.5 | 9.5 | 9.6 | 9.9 | 9.4 |

Table 2--Frequency distribution of maximum effective gust velocity per 3,000-foot interval of traverse at various altitudes. Based upon P-61C flights through Florida thunderstorms, 1946.

| Maximum effective gust velocity (fps) | Flight Altitude (ft-msl) | | | | | Total |
|---|---|---|---|---|---|---|
| | 6,000 | 11,000 | 16,000 | 21,000 | 26,000 | |
| 0- 4 | 586 | 937 | 1099 | 981 | 774 | 4377 |
| 4- 8 | 605 | 1017 | 1050 | 840 | 611 | 4123 |
| 8-12 | 372 | 538 | 498 | 414 | 266 | 2088 |
| 12-16 | 131 | 217 | 221 | 165 | 114 | 848 |
| 16-20 | 42 | 86 | 104 | 55 | 39 | 326 |
| 20-24 | 14 | 26 | 39 | 24 | 7 | 110 |
| 24-28 | 6 | 8 | 6 | 7 | 3 | 30 |
| 28-32 | 0 | 2 | 6 | 5 | 3 | 16 |
| 32-36 | 0 | 1 | 1 | 1 | 0 | 3 |
| 36-40 | 0 | 0 | 1 | 0 | 0 | 1 |
| 40-44 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total Number | 1756 | 2832 | 3025 | 2492 | 1817 | 11,922 |
| Total Miles Flown | 978.7 | 1557.3 | 1689.3 | 1401.1 | 1006.9 | 6633.3 |
| Mean of maximum gust velocity above 4 fps | 8.9 | 8.9 | 9.1 | 8.8 | 8.6 | 8.9 |

Table 3--Miles of flight necessary in thunderstorms to encounter a gust velocity greater than indicated. Based upon P-61C flights through Ohio thunderstorms, 1947.

| Altitude Feet MSL | Miles of Flight | | | | | |
|---|---|---|---|---|---|---|
| | 4.0 fps | 8.0 fps | 12.0 fps | 16.0 fps | 20.0 fps | 24.0 fps |
| 5,000 | 0.96 | 2.24 | 6.49 | 23.3 | 65.9 | 158 |
| 10,000 | 0.82 | 1.59 | 3.64 | 9.9 | 27.6 | 112 |
| 15,000 | 0.89 | 1.74 | 4.15 | 10.3 | 26.7 | 69 |
| 20,000 | 1.03 | 1.93 | 4.43 | 12.0 | 33.7 | 107 |
| 25,000 | 1.20 | 2.16 | 4.88 | 11.6 | 26.8 | 52 |

Table 4--Miles of flight necessary in thunderstorms to encounter a gust velocity greater than indicated. Based upon P-61C flights through Florida thunderstorms, 1946.

| Altitude Feet MSL | Miles of Flight | | | | | |
|---|---|---|---|---|---|---|
| | 4.0 fps | 8.0 fps | 12.0 fps | 16.0 fps | 20.0 fps | 24.0 fps |
| 6,000 | 0.84 | 1.73 | 5.07 | 15.8 | 48.9 | 163 |
| 11,000 | 0.82 | 1.77 | 4.58 | 12.7 | 42.1 | 142 |
| 16,000 | 0.88 | 1.93 | 4.47 | 10.8 | 31.9 | 121 |
| 21,000 | 0.93 | 2.09 | 5.45 | 15.2 | 37.9 | 108 |
| 26,000 | 0.97 | 2.33 | 6.07 | 19.3 | 77.5 | 167 |

In favor of this conclusion are the following:

1. In both seasons of flight, fewer large velocity gusts per mile were found at the 5,000 and 6,000-foot MSL levels.
2. The absolute maximum gust measured at the 5,000 and 6,000-foot MSL levels is much less than the maximum at any other level.
3. Pilot reports of turbulence encountered on each traverse through the thunderstorms in both seasons of flying show a minimum of moderate and heavy turbulence at 5,000 and 6,000 feet MSL

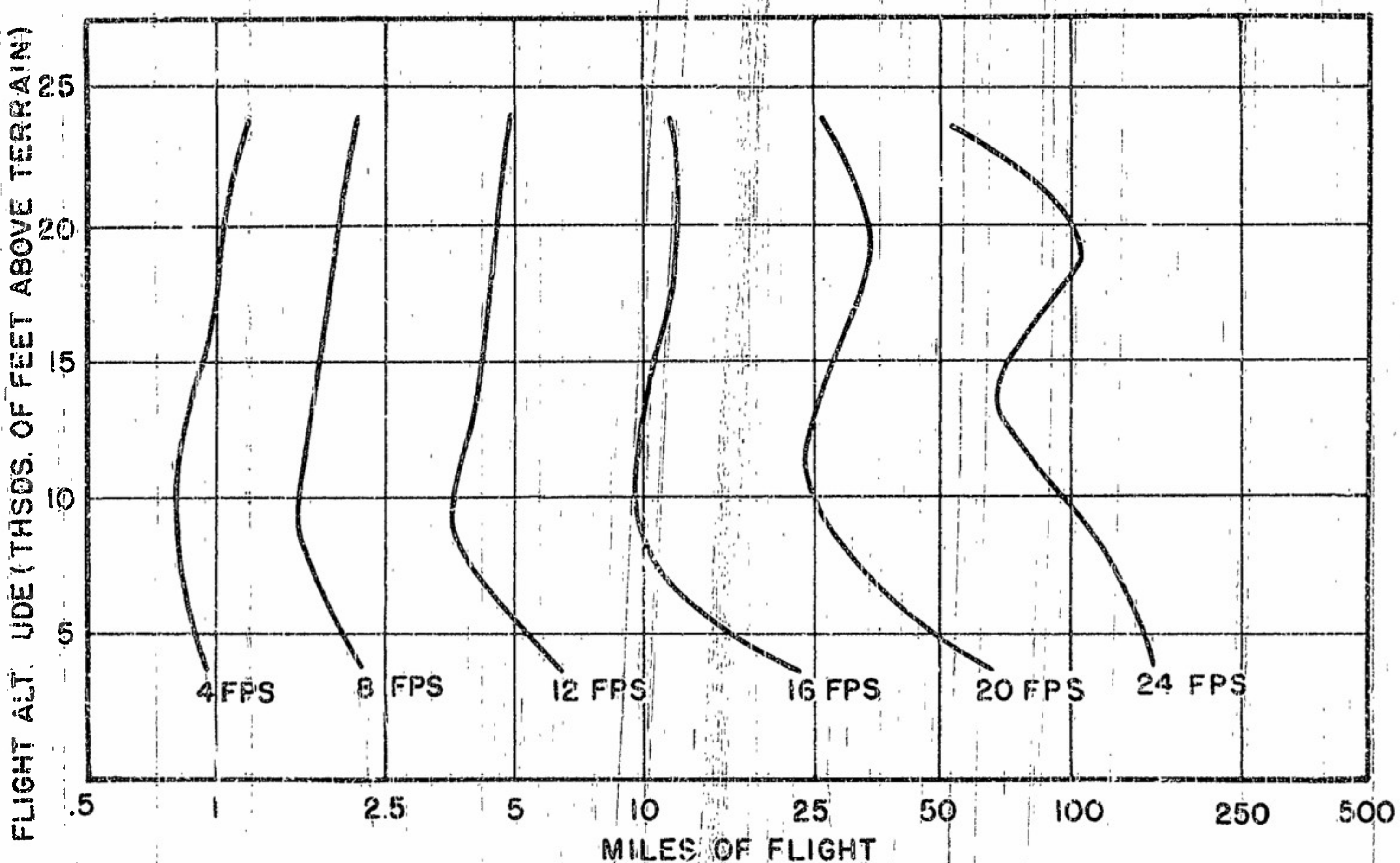


Fig. 2 -- Miles of flight necessary in thunderstorms to encounter a maximum gust velocity greater than indicated. Based upon P-61C flights through Ohio thunderstorms, 1947.

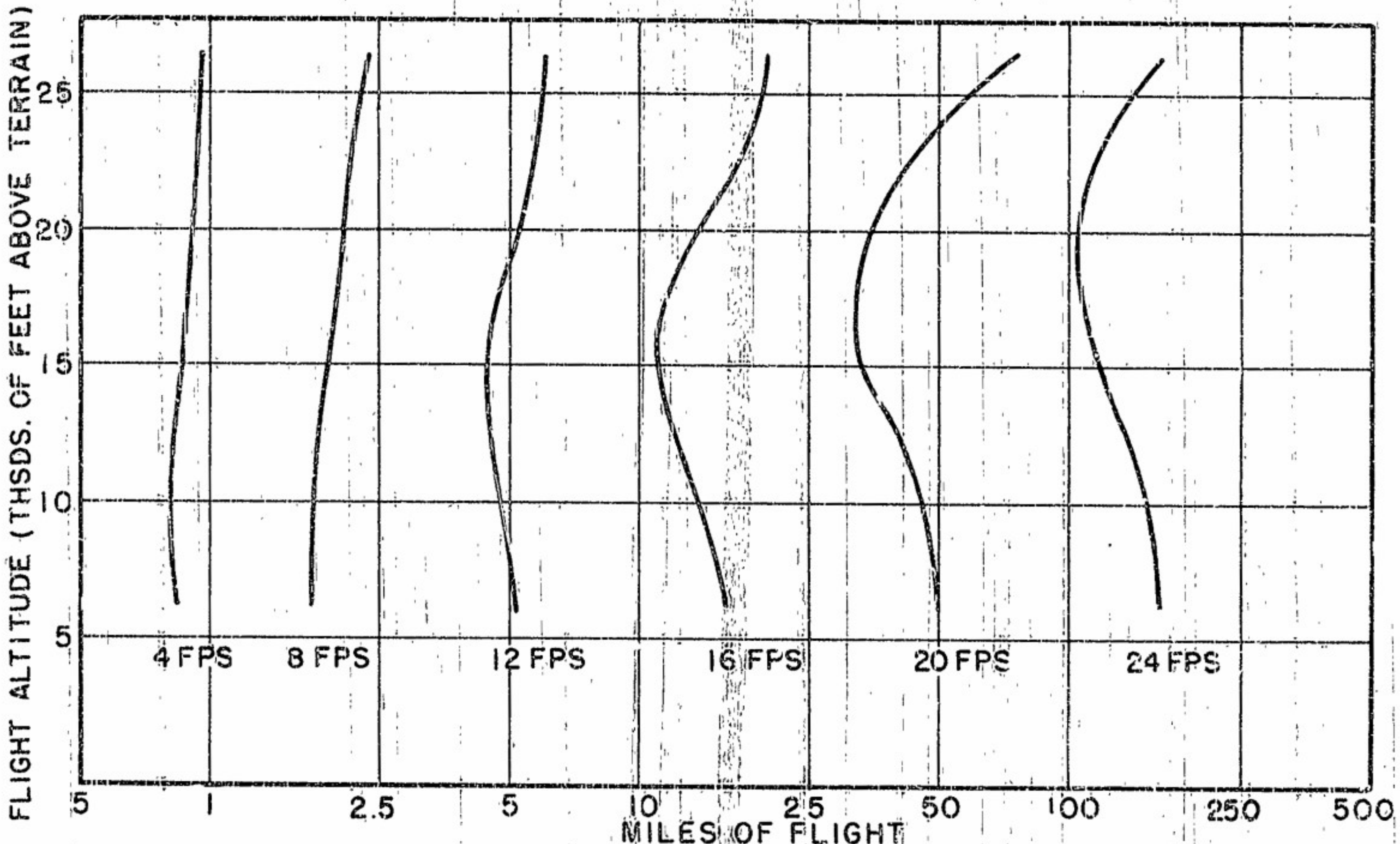


Fig. 3 -- Miles of flight necessary in thunderstorms to encounter a maximum gust velocity greater than indicated. Based upon P-61C flights through Florida thunderstorms, 1946.

4. At the surface, turbulence must reduce to zero; therefore, at some level between 5,000 feet and the ground there must be a distinct decrease in gust velocities. The shape of the curves on Figures 1 and 2 for the levels below 5,000 and 6,000 feet MSL are not known due to a lack of data for these levels. However, it is known that the Ohio data were taken, for the most part, 2,000 feet nearer the ground than were the Florida data and the frequency of high velocity gusts at the lowest flight level in Ohio is considerably less than the lowest level in Florida.

Turbulence above levels of Project Flight Operations

Another important problem is that of estimating the intensity of turbulence in thunderstorms above the levels flown by the Thunderstorm Project airplanes. By the use of a range-height-indicating radar, measurements have been made on the rate of growth of thundercloud tops, some of which have been observed to extend above 55,000 feet. These measurements show that the mean rate of growth up to an altitude about 10,000 feet below top of the individual storm increases with altitude. The rate of growth of these cloud tops is also a measure of updraft velocities. It is shown that there is a relationship between the gust and draft velocities (Fig. 4). Therefore, because of the lack of other more conclusive data, one might assume that the mean gust velocities increase with height in the thunderstorm cell, at least during the building stage, up to a level about 10,000 feet below the maximum height reached by the storm cell.

## Drafts within the Cloud

A draft is defined as a vertically-moving current or stream of air in the atmosphere. Although minor drafts are found in many weather conditions, it is in the thunderstorm that drafts reaching a speed great enough to cause

| SPEED OF MAXIMUM GUST (fps) | 4- 7.9 | 8-11.9 | 12-15.9 | 16-19.9 | 20-23.9 | 24-27.9 | 28-31.9 | 32-35.9 | 36-39.9 | 40-43.9 | 44-47.9 | 48-51.9 | 52-55.9 | 56-59.9 | 60-63.9 | 64.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ≥ 34.0 | | | 1 | | | | 1 | | | | | | | 2 | | |
| 32-33.9 | | | | | | | | 1 | | | | | | | | 1 |
| 30-31.9 | | | 1 | | | 1 | | | 1 | | | | | | | |
| 28-29.9 | | | | | 1 | | | 1 | | 1 | | | | 1 | | |
| 26-27.9 | | | | 2 | 3 | | 1 | | 2 | | 1 | 1 | 2 | 1 | | |
| 24-25.9 | | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | | | | 1 | | 1 |
| 22-23.9 | | | | 1 | 2 | 1 | 5 | 2 | 3 | 3 | 1 | | 1 | | 1 | 1 |
| 20-21.9 | 2 | 2 | 1 | 6 | 6 | 4 | 3 | 7 | 3 | 2 | 1 | | | | 1 | 2 |
| 18-19.9 | | 5 | 12 | 9 | 13 | 7 | 5 | 8 | 4 | 2 | 1 | 1 | 1 | | | 1 |
| 16-17.9 | 1 | 4 | 9 | 8 | 8 | 4 | 3 | 4 | 2 | 4 | | 1 | | | | |
| 14-15.9 | 4 | 8 | 13 | 11 | 10 | 10 | 12 | 11 | 4 | 2 | | | 3 | 1 | | |
| 12-13.9 | 5 | 16 | 11 | 9 | 14 | 13 | 10 | 2 | 3 | 1 | 2 | 1 | 1 | | 1 | |
| 10-11.9 | 3 | 13 | 26 | 17 | 18 | 9 | 16 | 7 | 8 | 4 | 2 | 1 | 1 | 1 | | |
| 8- 9.9 | 11 | 21 | 26 | 20 | 21 | 15 | 6 | 6 | 1 | | 1 | | | | | |
| 6- 7.9 | 11 | 27 | 21 | 18 | 11 | 3 | 2 | 2 | 1 | | | | | | | |
| 4- 5.9 | 9 | 17 | 7 | 7 | 4 | 6 | 3 | | | | | | | | | |
| 2- 3.9 | 1 | 6 | 4 | 2 | 1 | | | | | | | | | | | |

Total cases 812

SPEED OF DRAFT (fps)

Fig. 4--Relationship between draft velocity and velocity of maximum gust within the draft. Curve represents the regression function of mean maximum gust velocity on draft velocity. Correlation coefficient is 0.42. Based upon Ohio data.

major altitude displacements to airplanes are most commonly found. The drafts are directed upward during the early part of the storm, but as the storm grows older, downdrafts develop. Both the updrafts and downdrafts are usually continuous through all the altitudes flown by present-day airplanes. Individual drafts will last as long as 15 to 30 minutes, although during this time the speed will probably vary considerably. In general, the speed of the draft is greater than the speed of the gusts.

Under conditions of constant power, an airplane in level flight attitude will experience a change in altitude upon encountering a draft. The amount of the altitude change, in a known time interval, can be used to estimate the speed of the draft. Obviously, if the airplane is climbing or diving relative to the draft, the altitude change will not truly represent the draft. Air speed, however, can be used in detecting cases of nose-up or nose-down attitude, thereby making it possible to determine which altitude changes are due to drafts alone and which are due to combinations of attitude and draft or attitude alone.

It must be realized, however, that this problem of sorting out altitude changes due to drafts is a difficult one. The Project pilots were instructed to fly using a minimum of control and a constant throttle setting in order to make easier the evaluation of turbulence data. This control technique resulted in many instances where a pitch deflection caused by turbulence or draft gradient went uncorrected for several seconds.

In addition to unintentional pitch deflections, there were times when the pilot intentionally changed the attitude of the airplane, and there were a few instances when power settings were changed. Generally speaking, such positive control action was an attempt on the part of the pilot to alleviate the effects of a draft. Any change in attitude would cause a climbing or diving and could either increase or decrease the total altitude change. Even though comparison of the air speed and altitude traces allows one to determine such instances, it is difficult and at times impossible to estimate the magnitude of such an effect. If the data were restricted to only those cases during which the air speed remained constant, it is doubtful if the final sample would include more than 10 per cent of all drafts encountered. It is necessary, therefore, to adopt the procedure of computing as drafts all altitude changes where the air speed remains quasi-constant and all those where the air speed changes in such a manner as to cause the draft to appear weaker than it actually is. For example, one would accept as drafts altitude increases accompanied by air speed increases and vice versa. This procedure does not affect the usefulness of the data in fitting together the structure of the storm when draft magnitudes are less important than a knowledge of their existence, (Ref. 3), but it must be considered when applying the data to the problems of flying thunderstorms.

Using the above-outlined technique, it was possible to evaluate 1086 drafts from the records of two seasons of thunderstorm flying, (Tables 5 and 6). Subsequent analysis of the structure of the thunderstorm indicates that this probably represents less than 70 per cent of all drafts in excess of 10 fps encountered by the airplanes.

From Tables 5 and 6 one concludes that:

1. The maximum values of updrafts and downdrafts were measured at the middle and upper levels for both years.
2. In general, the mean updraft value was greater than the mean downdraft value at every level.
3. The mean updraft and downdraft values increased with height through the altitude range investigated.

The altitude displacement experienced by an airplane encountering a draft depends upon the draft width and speed and the speed of the airplane.* Generally speaking, the drafts encountered by Project airplanes

*Assuming the airplane is not climbing or diving.

Table 5--Actual number of drafts measured at various altitudes during Ohio operations, 1947.

| Draft Value (fps) | UPDRAFT Flight Altitude (thousands of feet) | | | | | DOWNDRAFT Flight Altitude (thousands of feet) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 5 | 10 | 15 | 20 | 25 | 5 | 10 | 15 | 20 | 25 |
| 0- 9.9 | 2 | 14 | 9 | 9 | 2 | 6 | 13 | 9 | 5 | 2 |
| 10-19.9 | 9 | 45 | 40 | 21 | 13 | 5 | 15 | 20 | 11 | 6 |
| 20-29.9 | 1 | 24 | 25 | 17 | 16 | 1 | 16 | 7 | 9 | 5 |
| 30-39.9 | - | 22 | 22 | 7 | 12 | - | 4 | 4 | 1 | 3 |
| 40-49.9 | - | 3 | 5 | 3 | 4 | - | 1 | 2 | - | 2 |
| 50-59.9 | - | - | 3 | 4 | 3 | - | - | 1 | - | 1 |
| 60-69.9 | - | - | 1 | - | 2 | - | - | - | - | - |
| 70-79.9 | - | - | - | - | - | - | - | - | - | 1 |
| 80-89.9 | - | - | - | - | 1 | - | - | - | - | - |
| 90-99.9 | - | - | - | - | - | - | - | - | - | - |
| Mean(fps) | 14 | 21 | 24 | 23 | 30 | 11 | 18 | 19 | 17 | 26 |

Table 6--Actual number of drafts measured at various altitudes during Florida operations, 1946.

| Draft Value (fps) | UPDRAFT Flight Altitude (thousands of feet) | | | | | DOWNDRAFT Flight Altitude (thousands of feet) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 6 | 11 | 16 | 21 | 26 | 6 | 11 | 16 | 21 | 26 |
| 0- 9.9 | 8 | 5 | 11 | 9 | 6 | 4 | 6 | 4 | 7 | 4 |
| 10-19.9 | 17 | 35 | 37 | 38 | 22 | 11 | 20 | 28 | 17 | 17 |
| 20-29.9 | 11 | 32 | 26 | 30 | 27 | 5 | 10 | 12 | 7 | 10 |
| 30-39.9 | 2 | 6 | 22 | 14 | 14 | 1 | 5 | 6 | 1 | 3 |
| 40-49.9 | - | 2 | 4 | 9 | 4 | - | - | 2 | 1 | 3 |
| 50-59.9 | - | 5 | 1 | 3 | 2 | - | - | - | - | 1 |
| 60-69.9 | - | - | - | - | 1 | 1* | - | - | - | - |
| 70-79.9 | - | 1 | 1* | 1 | - | - | - | - | - | - |
| 80-89.9 | - | 1 | - | - | - | - | - | 1* | - | - |
| 90-99.9 | - | - | 1* | - | - | - | - | - | - | - |
| Mean(fps) | 17 | 24 | 24 | 24 | 25 | 19 | 18 | 21 | 17 | 22 |

*Subject to question

would indicate that the altitude displacement that an airplane is likely to experience increases with height. For an airplane flying 180 mph, the displacement is not likely to exceed 2,000 feet although in exceptionally severe storms such as those flown by the Project on August 22, 1946 and August 5, 1947 upward displacements as great as 5,000 feet may occur. Displacements of this magnitude were rare (only 2 per cent of all the updrafts encountered caused displacements greater than 3,000 feet). The maximum downward displacement was 1400 feet.

Downdrafts Below the Cloud Base

Because of the large number of present-day flights below 5,000 feet and since every flight, regardless of cruising altitude, must pass through the region from the surface to 5,000 feet in take-off and landing, it is important to know something of the distribution of downdrafts below the base of the cloud and to investigate the possibility that an airplane flying at these levels may be forced into the ground by a thunderstorm downdraft. Unfortunately, the information for this region is very limited. The number of drafts computed by the Project for the 5,000-foot level was small, both because of the decreased frequency of strong drafts at this level and because the pilots flying at this level hesitated to allow their airplanes to be displaced a great distance, particularly by downdrafts.* The data available for studying drafts below the base of the cloud consist of the following:

1. Two flights during which the 5,000-foot plane was carried through the base of the cloud by the downdraft.

*This should not be interpreted to mean that the 5,000-foot gust data are also of reduced value. Gust computations do not depend upon a knowledge of draft values and are not affected by normal control movements.

2. One flight (7 August 1947) on which a plane probed the downdraft and rain area under a thunderstorm. On this flight, traverses were made at altitudes ranging from 1,000 to 4,000 feet above the ground.

3. Hundreds of cases of surface rainfall and the associated divergence which signify the existence and location of the downdraft.

Flight 19, 7 August 1947, was under what appears to be an average thunderstorm over the Ohio surface network. The range-height indicating radar showed tops of thunderstorms in the vicinity were reaching 38,000 feet; the storm flown reached a maximum height of 33,000 feet at 1449$^{h}$. Figures 5 and 6 show the radar outline of the cloud, the plane path and measured downdraft, and the surface rain pattern. Also shown is a trace of air speed and altitude records from which the draft values were computed. These data indicate that measurable drafts were encountered as low as 520 feet above the terrain. Figure 7 shows the time relationship between the measured drafts and the mean 5-minute rainfall rate and horizontal divergence at the surface. The first two traverses were made at a time when the rainfall and surface divergence show that the downdraft was increasing in size or speed or both. The last two traverses at higher altitudes were made at a time of decreasing rainfall and surface divergence and consequently after the downdraft had begun to diminish.

The significance of this single example depends somewhat on the manner in which it ties in with other more reliable data. For instance, it is easily seen that a downdraft approaching the ground must be accompanied by divergent surface winds. It is known that significant thunderstorm

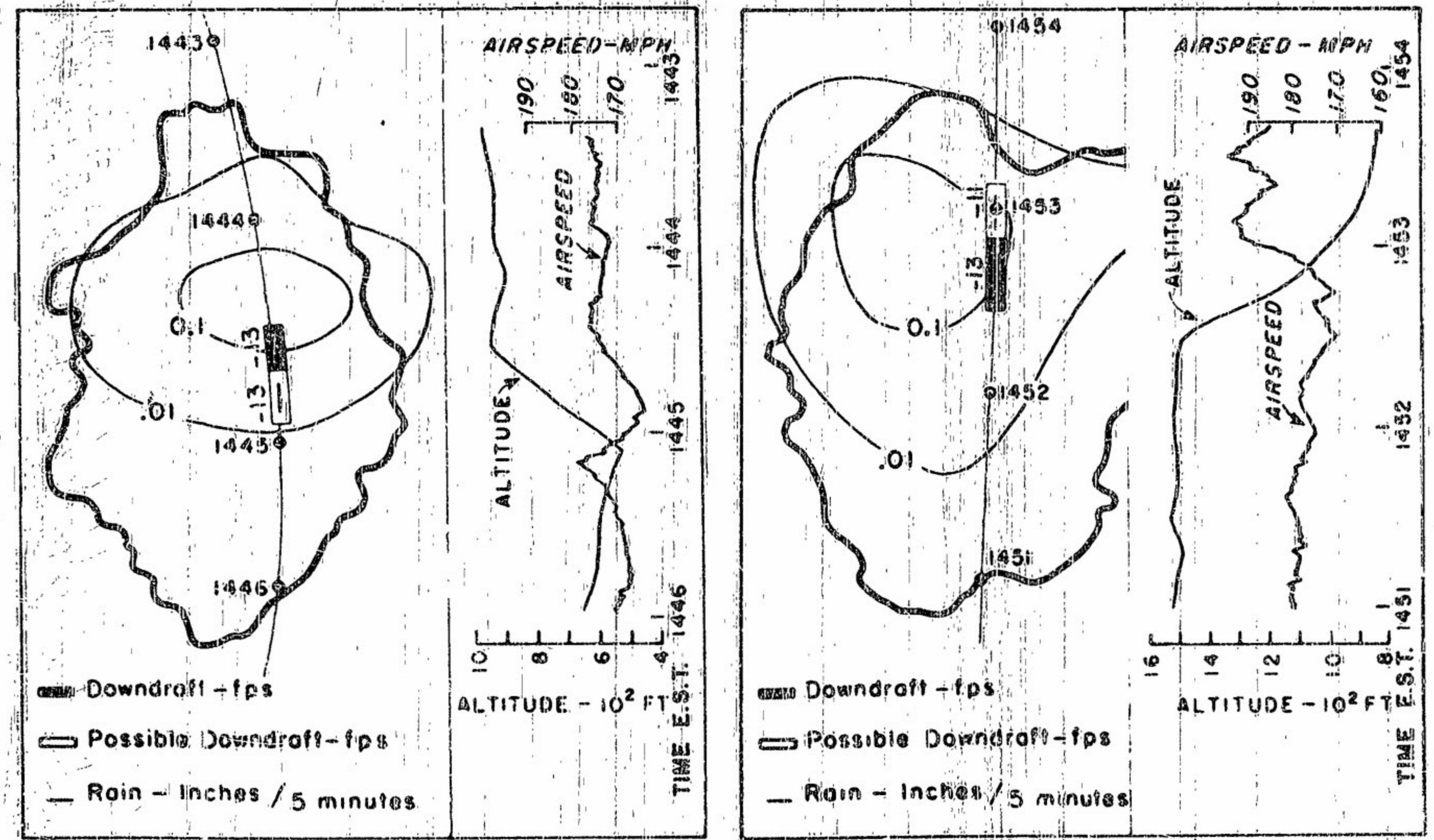


Fig. 5 --Radar echo, surface rainfall pattern, plane path and airspeed-altitude traces from which drafts were computed.

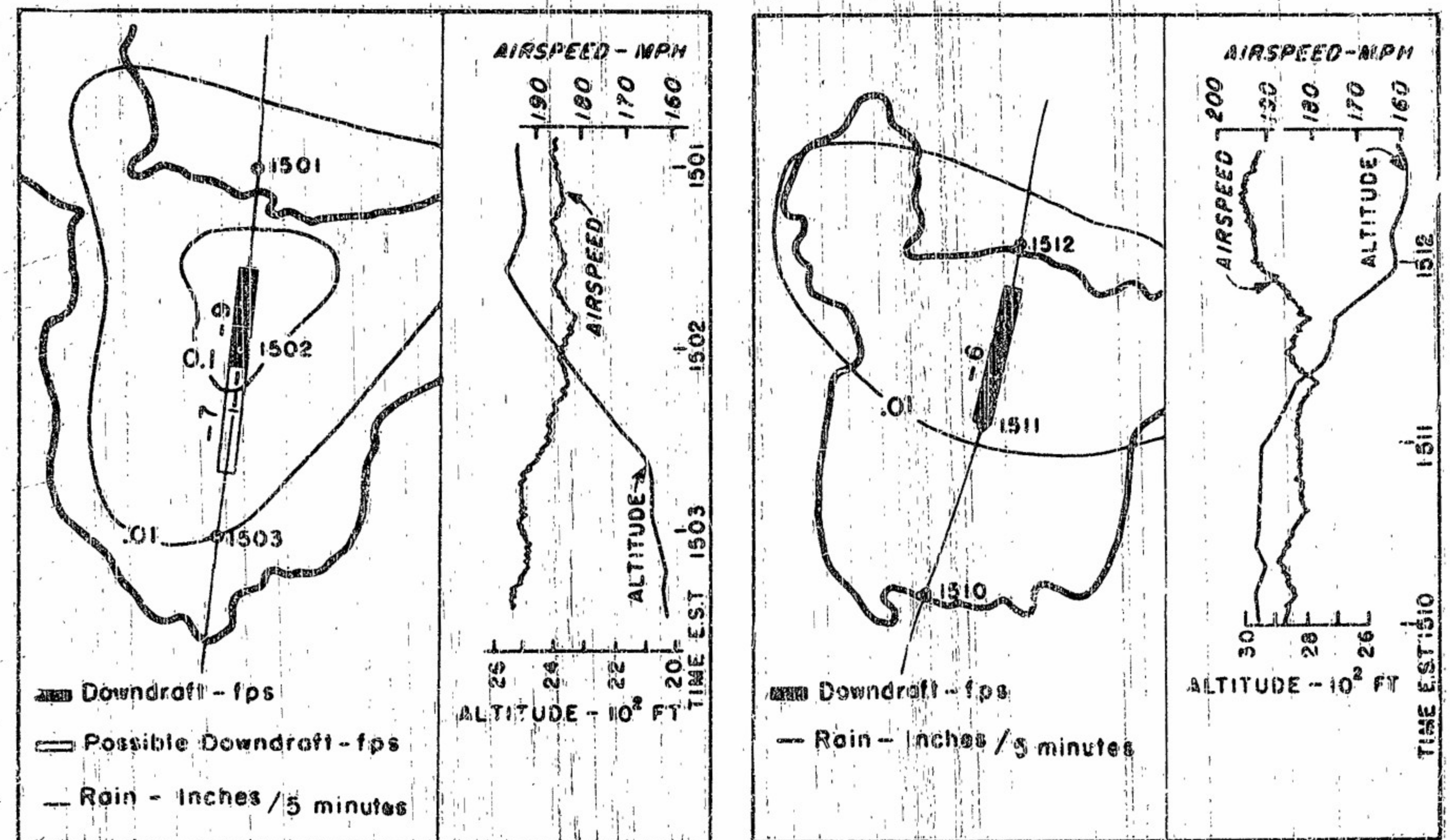


Fig 6-- Radar echo, surface rainfall pattern, plane paths and airspeed-altitude traces from which drafts were computed.

rainfall is always associated with surface divergence (Fig. 8). Since all downdrafts measured at 5,000 feet over the surface network were over a region of surface rainfall, one may conclude that significant thunderstorm downdrafts below the cloud base are associated with rain reaching the surface. These data indicate that high rates of rainfall are associated with high rates of surface divergence and therefore with high downdraft speeds.

On Flight 19, 7 August 1947, a downdraft of approximately 13 fps was measured on two traverses less than 1,500 feet above the ground. At the same time the surface rainfall averaged approximately 0.1 inches per 5 minutes and reached 0.3 inches per 5 minutes as a point maximum. The accompanying divergence in the rain area averaged about 5 $hr^{-1}$ and reached 10 $hr^{-1}$ as a point maximum. One would speculate that in thunderstorm conditions a repetition of these values would likewise be associated with a significant downdraft in the levels between the cloud and the ground.

The frequency of occurrence of these same conditions may be determined from the surface network records. It was found that rainfall rates of 0.3 inches per 5 minutes were reached or exceeded in 20 out of 54 Florida storms and in 10 out of 40 Ohio storms available for this study. In those storms where rain of this intensity was measured, it occurred 20 per cent of all the time that measurable rain was occurring. Point divergence of 10 $hr^{-1}$ was exceeded in 13 of 19 storms for Florida and Ohio for which divergence computations were made. Areas of strong divergence are always associated with areas of heavy surface rain.

As the downdraft approaches the ground it begins to spread out as a jet of water directed toward a flat plate forming a layer of relatively

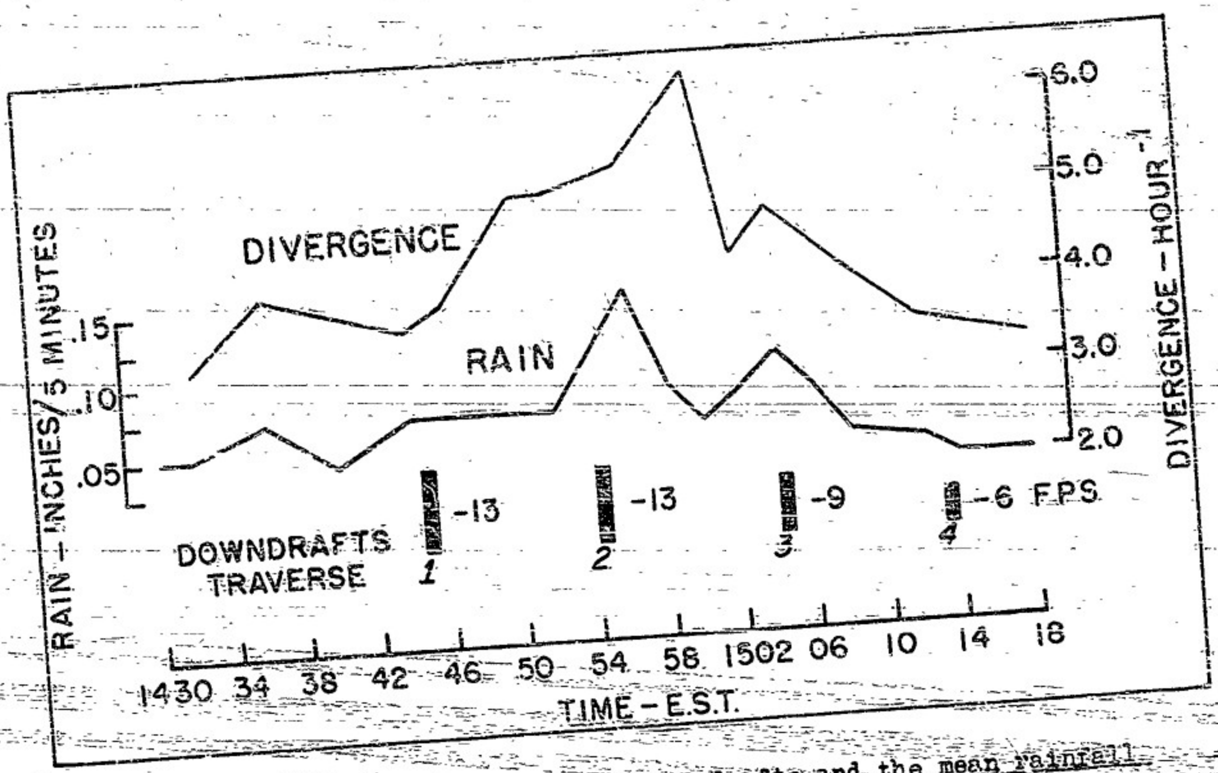


Fig. 7-- Relationship between the measured drafts and the mean rainfall rate and divergence.

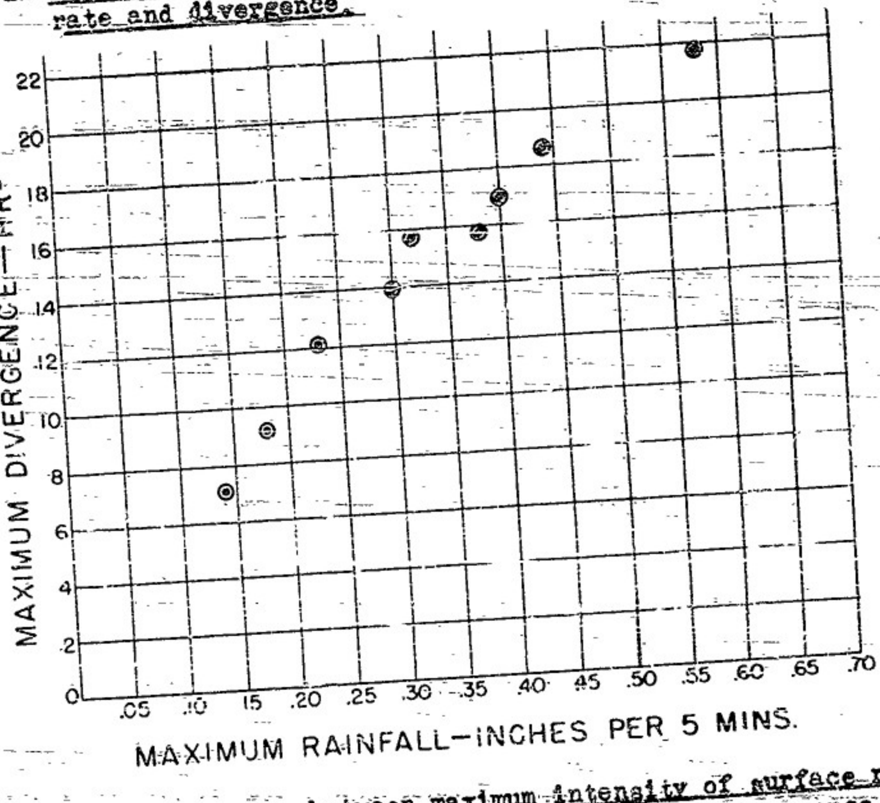


Fig. 8-- Relationship between maximum intensity of surface rain and maximum intensity of associated surface divergence.

cold air over the surface. The depth of this layer determines to a large extent, the possibility that an airplane can be forced dangerously close to the ground. Using balloons released around the storm, Byers and Hull (Ref. 4), found the top of this layer to average 2,500 feet and to vary from 1,000 to 5,000 feet above the terrain in seven cases computed.*

From considerations of the surface pressure increase resulting from a given depth of cold outflow air compared with observed pressure changes under the thunderstorm outflow, one is led to believe that in most cases the spreading cold air is restricted to the lowest 2,000 feet.

This leads us to believe that although the spreading of the downdraft in an average thunderstorm may start as high as 5,000 feet above the terrain, the downdraft continues predominately downward until it reaches an altitude of about 2,000 feet and then is retarded as the draft spreads out on the surface as a layer of cold air about 2,000 feet thick.

The question now comes up regarding what happens to an airplane encountering one of these downdrafts. From considerations based upon the size of surface rain patterns, length of measured drafts at the 5,000-foot level (Table 7), and the size of the structural cells, it is not likely that a downdraft would extend more than three miles and most downdrafts would be less than two miles in diameter. In a draft three miles in diameter with a speed of 20 fps (almost twice that measured on Flight 19) an airplane flying at 180 mph would be displaced downward about 1,200 feet providing no corrective action is taken by the pilot, in the 60 seconds it takes to traverse the draft. More than one draft may be encountered beneath a storm, although studies of storm structure indicate that it is not likely that two downdrafts would be separated by less than three miles (Ref. 3).

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*Two of these cases were computed after the original report had been completed. Work along these lines is continuing.

Table 7--Frequency distribution of downdraft extent as computed by NACA. Data taken by P-61C aircraft flying at 5,000 and 6,000 feet MSL during both seasons of operations.

| | DRAFT EXTENT (Thousands of feet) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-2 | 2-4 | 4-6 | 6-8 | 8-10 | 10-12 | 12-14 | 14-16 | 16-18 | 18-20 | 20 and over |
| Number of cases | 0 | 5 | 8 | 4 | 3 | 7 | 4 | 2 | 1 | 1 | 0 |

Based upon these data, it would not be expected that a modern military or commercial airplane flying 2,000 feet above the terrain would be carried into the ground.* The lack of data prevents one from drawing more definite conclusions regarding the zone below 2,000 feet, although we do know that a P-61 was displaced from 950 feet down to 520 feet in a thunderstorm downdraft.

On another occasion a pilot flying at the 5,000-foot MSL level reported being carried through the base of the cloud by the downdraft (Fig. 9). In this instance, part of the altitude lost resulted from a diving attitude of the airplane.

More important than the total altitude lost in a downdraft is the possibility that an airplane carried down over hilly country would not have a sufficiently high rate of climb to avoid terrain obstacles in the path of the airplane.

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*It is well to point out the possibility that a pilot attempting to prevent his plane from being carried downward may place the plane in sufficiently nose-high attitude that a gust may cause the plane to stall with insufficient altitude for stall recovery. The consequences of flying a light airplane or lighter-than-air craft into the area of heavy thunderstorm rain with its attendant downdraft is obvious.

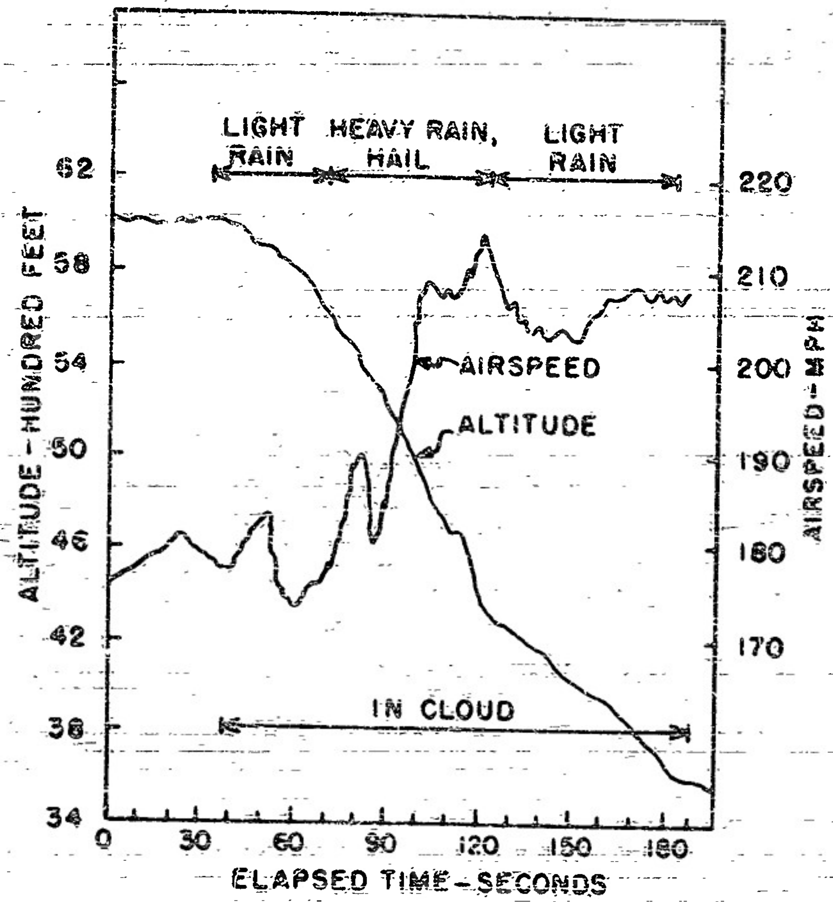


Fig. 9--Airspeed and altitude changes that occurred on a flight through a thunderstorm, August 14, 1947.

## Interrelation Between Turbulence and Precipitation

It was stated in "A Report on Thunderstorm Conditions Affecting Flight Operations" that there is a direct relationship between the intensity of the precipitation and turbulence reported by the aircrews. It was pointed out, however, that a report of rain from an airplane does not necessarily mean water falling to the ground, for it may be suspended in, or ascending with, the updrafts. This is an important fact from the standpoint of the possibility of radar being able to help detect the more turbulent areas.

However, in presenting material that may be of use to pilots flying at or near the cloud base there is an objection to using reports at higher levels where one cannot tell whether the water encountered is actually falling rain. To correct this shortcoming the study reported in Weather Bureau Technical Paper No. 7 was repeated (Table 8) using Ohio data for only the 5,000-foot level.

Table 8--Relationship between simultaneous occurrences of various intensities of precipitation and turbulence for 5,000-foot altitude. Based upon 1947 data from Ohio thunderstorms.

| Precipitation Intensity | Turbulence Intensity | | | | |
|---|---|---|---|---|---|
| | Heavy | Moderate | Light | None | Unclassified |
| Heavy | 10 | 21 | 28 | 14 | 23 |
| Moderate | 0 | 10 | 31 | 8 | 29 |
| Light | 0 | 7 | 65 | 17 | 40 |
| None | 0 | 3 | 17 | 0 | 0 |
| Unclassified | 4 | 23 | 27 | 1 | 0 |

It seems that there can be little doubt but that reports of heavy rain at this level actually represent rain in the accepted sense. It can be seen that heavy rain accompanied the heavy turbulence in every case for which simultaneous reports are available. Furthermore, there was a maximum of light turbulence with light precipitation, although many cases of heavy rain and light turbulence were noted. It therefore seems that regardless of altitude, areas of heavy turbulence and areas of heavy rain are coincident. To reduce the element of subjectivity inherent in these reports, the mean maximum gust velocity for the period 10 seconds before and after each report of rain intensity was calculated. The results show that the mean maximum gust velocity during periods of heavy rain was 6.3 fps, and during light rain it was only 3.9 fps.

These facts support the enthusiasm which many recent papers have expressed in viewing the use of radar in avoiding areas of turbulence in convective clouds. Atlas (Ref. 2) and Langille, Gunn and Palmer (Ref. 7) have laid the foundation for a quantitative rainfall intensity indication from the radar. Press and Binckley (Ref. 8) using turbulence data taken on the Thunderstorm Project, have reported that the gust velocities inside the radar echo are considerably higher than in the area more than two miles beyond the echo. Although many organizations such as Air Weather Service and All Weather Flying Division of U. S. Air Force, and various airlines are investigating the use of radar as an aid in meeting the problem of turbulence, some of the most encouraging of recent reports are those of American Airlines (Ref. 1).

Conclusions

An analysis of the gust and draft data taken by the Thunderstorm Project in storms of Florida and Ohio indicates the following:

1. The level of the least turbulence between 4,000 and 26,000 feet above the ground in a thunderstorm is at or near 4,000 feet which is usually near the base of the cloud.
2. The data indicate that there is a significant relationship between gust velocity and gust frequency. There is also a relationship between the speed of drafts and the speed of the associated gusts.
3. The data indicate that the updrafts and the associated turbulence in a thunderstorm cell may increase with height up to a level of about 10,000 feet below the maximum height reached by each particular storm cell.

4. The average thunderstorm in Ohio contains greater turbulence, in the levels flown by the project, than the average thunderstorm in Florida.
5. The altitude displacements caused by thunderstorm drafts increase with height at least to a level 25,000 feet above the storm base.
6. Significant downdrafts exist beneath the cloud base. These are found in the areas of heavy rain. It is not likely that a thunderstorm draft will force a modern military or commercial airplane, if properly flown, dangerously close to level ground; however, the downdraft, even at low levels, may be dangerous for a light airplane with its low rate of climb and slow speed.
7. Areas of highest water concentration are the areas of heaviest turbulence. This lends support to the growing list of evidence that radar can be used to avoid areas of excessive turbulence in convective clouds. In flights below cloud bases, the heaviest turbulence will be found where the darkest rain columns are seen.

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## REFERENCES


1. American Airlines, 1948: Flying Around and Through Thunderstorms Using Airborne Radar. Flight Test Report 58.

2. Atlas, David, 1947: Some Experimental Results of Quantitative Radar Analysis of Rain Storms. USAF AMC Report AWNW 7-4 Part 11.

3. Byers, H. R. and Braham, R. R., 1948: Thunderstorm Structure and Circulation. J. Meteor., Vol. 5, No. 3.

4. Byers H. R. and Hull, E. C., 1949: Inflow Patterns of Thunderstorms as Shown by Winds Aloft. Bull. Am. Meteor. Soc., Vol. 30, No. 3, 90-96.

5. Harrison, H. T., 1941: Prefrontal Squall Lines. United Air Lines Meteor. Dept., Circular No. 16.

6. Holford, J. F. and Morris, D. E., 1947: An Interim Report on High Altitude Gust Investigation. Royal Aircraft Establishment, Report No. AERO 2235.

7. Langille, R. C., Gunn, K. L. S. and Palmer, W. M., 1948: Quantitative Analysis of Vertical Structure in Precipitation. Defense Research Board. Dept. of National Defense, Canada.

8. Press, H. and Binckley, E. T., 1948: A Preliminary Evaluation of the Use of Ground Radar for the Avoidance of Turbulent Clouds, National Advisory Committee for Aeronautics.

9. Rhode, Richard, V., 1937: Gust Loads on Airplanes, SAE Jour., Vol. 40, No. 3, pp. 81-88.

10. Rhode, Richard V. and Donely, Philip, 1944: Frequency of Occurrence of Atmospheric Gusts and of Related Loads on Airplane Structures. NACA ARR No. L4121.

11. Rhode, Richard V. and Lundquist, Eugene E., 1931: Preliminary Study of Applied Load Factors in Bumpy Air. NACA TN No. 374.

12. U. S. Weather Bureau Thunderstorm Project, 1946: Operation and Activity of the Thunderstorm Project to September 20, 1946. Report No. 1 to Chief of U. S. Weather Bureau.

13. U. S. Weather Bureau Thunderstorm Project, 1947: Operation and Activity of the Thunderstorm Project, April 1 - October 1, 1947. Report No. 3 to Chief of U. S. Weather Bureau.

14. White, F. D., 1946: The Thunderstorm Project: Operational Report on Phase I, Bull. Am. Meteor. Soc., Vol. 27, No. 9, 549-550.

15. White, F. D., 1948: The Thunderstorm Project: Operational Report on Phase II, Bull. Am. Meteor. Soc., Vol. 29, No. 4, 192-194.