Technical Paper No. 7

A Report on Thunderstorm Conditions Affecting Flight Operations

PUBLISHED CONTRIBUTION NO. 4 OF THE THUNDERSTORM PROJECT

THUNDERSTORM PROJECT, CHICAGO, ILL.

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Preface

This report is preliminary in nature, since the analysis of data gathered by the Thunderstorm Project is only about half completed. The report is issued at this time in order to make available in the beginning of the 1948 thunderstorm season information and conclusions obtained thus far for possible application to this season's thunderstorm problems of commercial and military flight operators. It is anticipated that results of new or more complete studies of the data will be made available later either in the form of addenda to this report or in a revision of it.

The Thunderstorm Project and its system of observations and analysis have been described in other publications referred to at the end of this report. Although the general planning and direction of the program and the analysis of the data have been the responsibility of the Weather Bureau, the contributions of other agencies can hardly be overemphasized. The main facilities for the observation program, including such major items as airplanes and crews, radars, operating bases with personnel and equipment, were provided by the Air Force. The National Advisory Committee for Aeronautics provided instrumental equipment and technical supervision for measuring and evaluating gust and draft data from the airplane flights. Both the Air Force and NACA participated and consulted in the analysis. The U. S. Navy contributed ground equipment and electrical measurements and assisted financially in the observation and analysis work. Assistance in analysis has been obtained from staff members of the University of Chicago.

Thunderstorm Project personnel mainly responsible for the compilation of this report are Roscoe R. Braham, Jr., Harry Moses, Louis J. Battan, and Harry L. Hamilton, Jr., of the Weather Bureau, and Capt. Fred W. Pope of the Air Weather Service, U. S. A. F. Other members of the Project who participated in its preparation are listed at the end of the report under "Acknowledgment."

Horace R. Byers,
Director, Thunderstorm Project.

Chicago., Ill, *April 7, 1948.*

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A Report on Thunderstorm Conditions Affecting Flight Operations

Introduction

The problem of flying through thunderstorm conditions has been one of major concern since the advance of commercial and military aviation to the point where flight activities are not confined to periods of good weather. With the increased importance of air travel and the increased speed of airplanes, the possible effects of the conditions likely to be encountered in thunderstorms have been the subject of considerable attention.

The need for more information on the problem was one of the reasons for the establishment of the Thunderstorm Project[1] (ref. 1). Careful consideration by the advisers of this research group led to the conclusion that its first goal must be the determination of the physical structure and processes of the thunderstorm. With an exact knowledge of the characteristics of the storm, their possible effects on an airplane could be more carefully evaluated. In addition to the above aspects, thought must also be given to the different operational and structural limits of various airplanes, and to the role a pilot can play in augmenting the stresses atmospheric turbulence places on the airplane structure.

To gather data for its study, the Thunderstorm Project observed storms in Florida during the spring and summer of 1946 and in Ohio during the spring and summer of 1947. Measurements were made with a surface meteorological network, surface radar, instrumented airplanes, rawins, rawinsondes, and radiosondes. The airplane used was the P–61C, Northrop "Black Widow,"[2] which carried a crew consisting of pilot, radar operator, and weather observer.[3] These airplanes traversed the thunderstorms at altitudes from 5,000 to 26,000 feet and furnishel a most important source of information. They were instrumented to measure and record quantities from which gust and draft velocities can be computed and motion-picture records of the flight instruments were obtained. During the 1947 season, a wire recording of the air crew's comments and all radio transmissions, including a timing signal, was made in each airplane. Details of the ground installations, of the

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[1] A joint project of the Air Force, Navy, National Advisory Committee for Aeronautics, and the Weather Bureau, under the directorship of H. R. Byers.

[2] Air Force night fighter: Take-off weight about 30,000 lbs.; wing area, 662 sq. ft.; wing loading, 45.7 lbs./sq. ft.; span, 66 ft.; length, 49 ft.; two 2,000 h. p. engines; cruising speed, 205 IAS at 1,900 r. p. m. and 35.5 in. manifold pressure; stalling speed, 125 IAS with cruise power, wheels and flaps up.

[3] Weather observer was not present for the Florida flights.

other special instruments carried by the airplanes and the operating procedures have been described in previous reports (refs. 2, 3, 4, and 5).

Analysis of the records assembled by the Project now gives a better picture of the structure of the thunderstorm than has heretofore been available. The large number of controlled airplane flights through Florida and Ohio thunderstorms makes possible a statistical treatment of the weather elements encountered and the forces imposed on the airplanes by the vertical component of the air motions within these storms. In the statistical analysis, where possible, emphasis has been placed on the altitude distribution of the phenomena, for in most cases selection of flight altitude is one of the few parameters over which a pilot can exercise control. Other material of operational interest has been analyzed and is presented in a manner most suited to the nature of the data.

The Thunderstorm as It Affects Airplane Flights

Vertical extent.—Before considering the flight path through the average thunderstorm, it is necessary to first examine its vertical extent to determine the possibility of flying over the top.

Prior to the introduction of radar into the field of meteorological observation, it was impossible to give a reliable estimate of the maximum vertical extent of thunderstorms. In many cases the tops of the storms cannot be visually observed because of the presence of stratified clouds either near the base of the cloud or at some higher level. The use of airplanes for measuring cloud tops is feasible provided they do not extend above the ceiling of the airplane. The majority of thunderstorms, however, extend above 30,000 feet, with the result that the cloud top can only be estimated when conventional airplanes are used.

By using a radar set with a range-height-indicator (RHI), it was possible to obtain direct measurements of the tops of many thunderstorms in Ohio. The characteristics of radar as an instrument for observing clouds are such that there will be closer correspondence between the radar-measured top and actual cloud top during the developing stage of a thunderstorm than during the dissipating stage. This results from the fact that during the former a large quantity of snow particles and water droplets are carried to the higher portions of the cloud by the strong updrafts, while, in the latter, the absence of strong updrafts permits the precipitation of the large hydrometeors to the lower levels, leaving only small particles in the upper part.[4] Since it is improbable that the reflectivity of the upper extremity of the cloud is sufficiently high to produce an echo on the 'scope, the radar-indicated top will be lower than the actual top in almost every case when the radar set used has a narrow vertical beam. The effect of range (distance between radar set and storm) is such as to make the difference between actual and radar-measured tops greater as the distance between the thunderstorm and radar site increases.

The data used for this study were extracted from the photographic records of the range-height-indicator of a radar set AN/TPS–10.[5] In normal opera-

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[4] See refs. 6, 7, and 8 for a detailed discussion of the use of radar for storm detection.

[5] See ref. 5 for technical characteristics.

tion, the radar antenna scanned vertically 60 times per minute while rotating through a particular azimuthal sector at a rate of approximately one-third of a revolution per minute. The 'scope was photographed every 2 seconds. The average time between radar observations of the same cloud ranged from 1 to 3 minutes, thus permitting an accurate determination of the maximum height reached by any storm.

In many cases the clouds were not observed visually and it was therefore impossible to verify that they were thunderstorms as defined by Circular N. However, since the airplane crews reported that when a cloud was a thunderstorm it extended to the highest flight level—26,000 feet—it was arbitrarily decided that for this study only those echoes which extended to at least 25,000 feet would be considered as thunderstorms. On those occasions when the storms were located within 30 miles of the radar site, the echoes often extended to the upper limit of the 'scope and were cut off at that level. When this occurred 1,000 feet were added to the altitude of the indicated tops, although in many cases they appeared to extend considerably higher.

Tabulations were made of the heights of all storms occurring within 40 miles of the radar site on 11 selected days. The selection was made so that the sampling would include frontal, squall-line, and air-mass storms. Only 1 day on which frontal thunderstorms occurred was included, since the radar set used for these observations was not operating satisfactorily until late in July and most of the active cold fronts passed over the region prior to this date.

Table 1 gives a frequency distribution of the maximum vertical extent of the 185 cases observed. Each one of these cases represents a thunderstorm which may have contained many cells. If two developing thunderstorms merged and continued developing, the resultant echo was considered as one thunderstorm.

TABLE 1.—*Frequency distribution of the maximum vertical extent of thunderstorms detected by AN/TPS–10*

Type	Height (thousands of feet)							Mean height 1,000 ft.	Number of days	Number of storms
	25.0–29.9	30.0–34.9	35.0–39.9	40.0–44.9	45.0–49.9	50.0–54.9	55.0–59.9			
Air mass	22	26	19	17	14	11	2	37.2	5	111
Squall line	16	7	15	13	11	8	0	37.7	5	70
Frontal	[1] 1	1	0	0	[1] 2	0	0	37.8	1	4
Total	39	34	34	30	27	19	2	37.4	11	185

[1] These thunderstorms at ranges from 43 to 56 miles.

The storms are separated into three categories according to type. The number of days of each type as well as the arithmetic means of the maximum height are also included. The mode of the total distribution is in the 25,000- to 29,900-foot interval; however, more than 50 percent of the cases extended above 35,000 feet. The mean maximum radar top, when all storms were considered, was about 37,000 feet. An average value of the frontal thunderstorms is not significant since there are only four cases. The absolute maximum height reached was measured at 56,000 feet. For emphasis, it is repeated that these figures give the radar-measured top and that the actual cloud probably extends somewhat higher.

These data indicate that the "over the top" technique of flying for the avoidance of weather is not feasible with most present-day airplanes. It is therefore necessary to consider the flight path through the storm. In doing this we must take into account the structure, gust, and draft conditions, and other weather phenomena likely to be encountered in the interior.

Structure.—Based upon the storms studied,[6] it has been found that all thunderstorms are fundamentally similar both in structure and the weather elements contained therein. Structurally, the thunderstorm contains many centers of convective action, which are called "thunderstorm cells" (ref. 9). Each cell may develop more or less independently of those adjacent to it. The evidence indicates that each cell passes through three different stages in its life cycle. The progression to suceeding stages depends upon the formation and fall of rain and the entrainment of the surrounding air into the cloud. The adopted designation and predominant characteristics of each of the stages are as follows:

1. The cumulus stage—in which the cell contains only updraft from the base to the top of the cloud.
2. The mature stage—in which the fall of raindrops initiates a local downdraft in a part of the region in which updrafts had existed.
3. The anvil stage—in which the entire lower part of the cell contains a gentle downdraft. The upper part of the cell contains drafts of negligible velocities.[7]

Analysis of rawinsonde data has indicated that entrainment definitely exists and has revealed some of the results of this phenomenon. A study of the vertical distribution of horizontal convergence around a thunderstorm shows that the major portion of the air is brought into the cell through the sides rather than up through the base. The entrainment and mixing of cooler and drier air results in an updraft lapse rate which is steeper than the moist adiabat through the cloud base. Its proximity to the lapse rate of the environment facilitates the "triggering" of the downdraft by the rain after it begins to fall through the existing updraft. The denser, descending air spreads out over the surface,[8] and, behaving similarly to a cold front, contributes to the development of additional thunderstorm cells (ref. 10).

The data from which the structural features of the thunderstorm cell were determined further indicate that most significant turbulent motions and large-scale vertical motions are confined within individual cell boundaries. A large-scale vertical current of air, continuous over several thousand feet of altitude (occasionally 30,000 feet or more) is known as a draft. Gusts are smaller-scaled discontinuities in the velocity field of the thunderstorm. The gusts that affect the airplane have horizontal extents of from 30 to 300 feet. In traversing the storm, the drafts that are encountered tend to carry the airplane up or down but the gusts impose a series of accelerations that cause

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[6] 70 hours of "in-cloud" time on 76 missions were flown in Florida and Ohio. 179 storms that passed over the surface network during the two seasons were selected for study.

[7] For complete discussion of structure of the thunderstorm cell, see ref. 9.

[8] See page 17.

the "bumpiness" characteristic of cumuliform clouds. Since these turbulent motions are of concern to the aviator, it is of value to examine the frequency distribution of gusts and drafts.

Gusts.—It is often assumed that the severity of a storm, as far as a flight through the storm is concerned, is determined by the magnitude and frequency of the turbulent motions. Table 2 is a tabulation of the effective velocity [9] of the maximum gust encountered in each 3,000-foot interval of traverse by the airplanes in the Florida thunderstorms.

As might be expected, this table shows that, regardless of altitude, low-gust velocities occur more frequently than do high-gust velocities. The table also indicates that the mean of the $U_{e\,max.}$ varies little with altitude.

However, the mean of the $|U_e|_{max.}$ does not tell the complete story as far as flying is concerned. If it be assumed that the more frequent, low-velocity gusts do not contribute as much to the total discomfort of the passengers and do not stress the airplane structure so severely as those of higher velocity, it is found that there is a significant variation in the distribution of the turbulence with height.

TABLE 2.—*Frequency distribution of maximum effective gust velocity* ($|U_e|_{max.}$) *per 3,000 feet of traverse at various altitudes*

[Based upon P-61C flights through Florida thunderstorms, 1946]

$\vert U_e\vert_{max.}$ (fps)	Flight altitude (thousands of feet)					Total
	6	11	16	21	26	
2–4	243	374	419	319	208	1, 563
4–6	310	528	523	473	325	2, 159
6–8	295	478	527	367	286	1, 953
8–10	235	308	265	258	158	1, 224
10–12	137	217	233	156	108	851
12–14	73	129	126	107	83	518
14–16	58	84	95	58	31	326
16–18	23	49	53	30	26	181
18–20	19	35	51	25	13	143
20–22	10	18	26	17	5	76
22–24	4	7	13	7	2	33
24 and over	6	11	13	13	6	49
Total	1, 413	2, 238	2, 344	1, 830	1, 251	9, 076
Mean (fps)	7. 8	7. 8	7. 9	7. 7	7. 5	----------
Miles flown	978. 7	1, 556. 3	1, 689. 1	1, 401. 1	1, 006. 9	6, 632. 1

In figure 1 is plotted the altitude variation of the frequency of gusts with effective gust velocities greater than a minimum value. The large number involved made it impractical to compute and use in this study all the gusts that occurred. Instead, each traverse was divided into increments of 3,000 feet and the maximum effective gust velocity for each such interval was used to represent the gust velocities for that interval. NACA has evaluated the entire gust count for many of the flights and has found that the use of the maximum for each interval provides a representative sample.

It is apparent that there is a definite maximum frequency of the higher-velocity gusts in the altitudes near the freezing level, which is at about 16,000 feet in tropical air masses in summer.

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[9] See ref. 11 for definition of effective gust velocity.

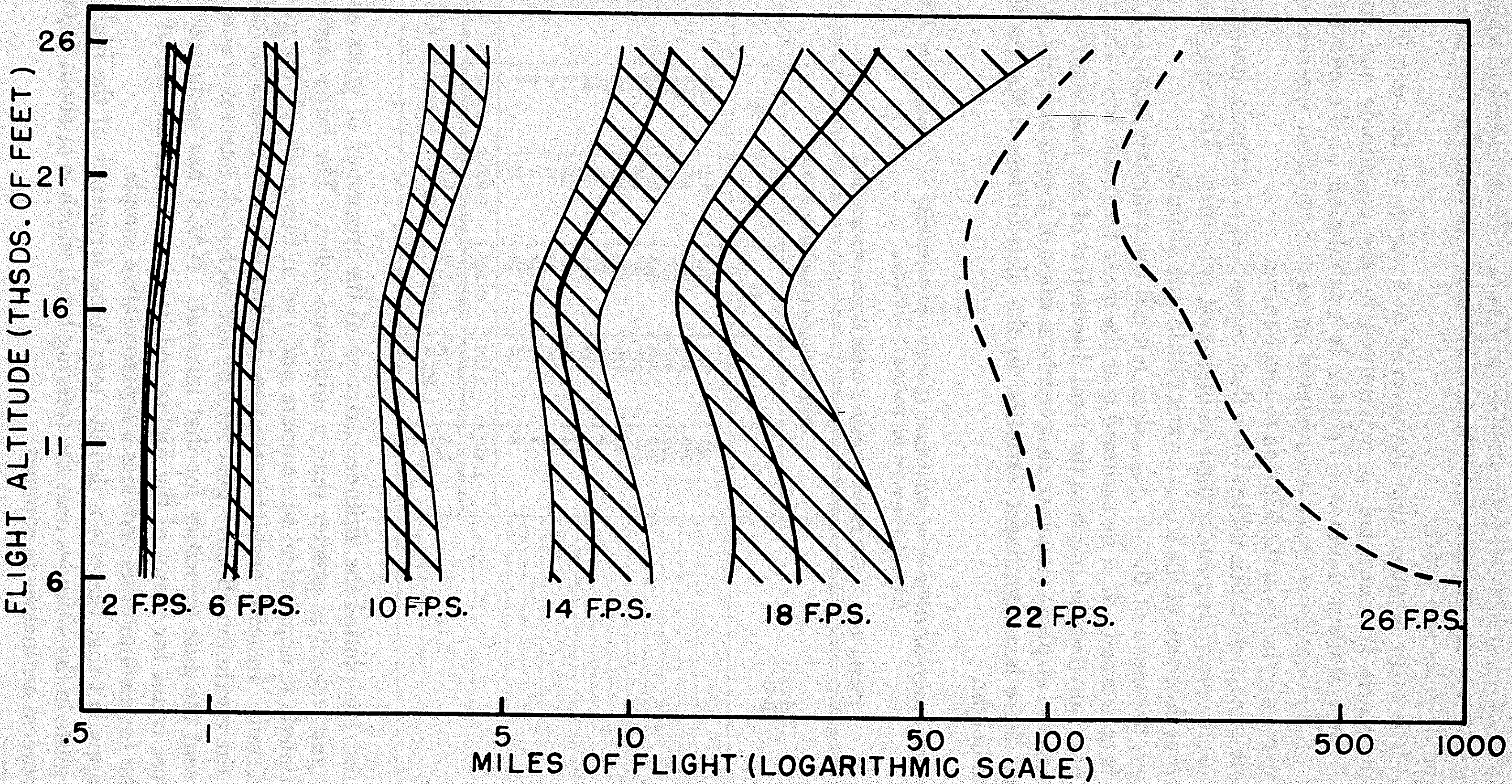

FIGURE 1.—Miles of flight necessary in thunderstorm conditions to encounter a maximum effective gust velocity greater than indicated. Hatched areas are the 99.7 percent (3 σ) confidence bands. Dashed-line curves are based on data too sparse to allow computation of confidence bands.

Considering the significance of figure 1, two questions present themselves: (1) Whether one could expect the maximum gust velocity, without regard to the frequency of the gusts within the interval, to determine the severity of the turbulence; (2) whether the Project air crews agreed that there was a maximum of heavy turbulence in the middle levels of flight.

There is some limited evidence that using only the maximum gust velocity gives a satisfactory summarization of the severity of the turbulence. Tables 3 and 4 show the number and relative frequency of air-crew reports of intensities of turbulence at the various altitudes in the storms over Florida and Ohio. It is significant to note that for the Florida storms, the highest frequency of reports of heavy turbulence was for the 16,000-foot level. In Ohio the percentage frequency of reports of heavy turbulence was about the same for 15,000 feet and above.

TABLE 3.—*Frequency (N) and percentage distributions of various turbulence intensities at a given altitude*

[Based upon 1946 data from Florida thunderstorms]

Turbulence intensity	Flight altitude (feet)									
	6,000		11,000		16,000		21,000		26,000	
	N	%	N	%	N	%	N	%	N	%
Light	51	53	56	43	47	37	51	44	42	52
Moderate	15	16	39	30	32	25	26	23	14	17
Heavy	22	23	26	20	36	28	29	25	17	21
Unclassified	8	8	10	7	13	10	9	8	8	10
Total	96	100	131	100	128	100	115	100	81	100

TABLE 4.—*Frequency (N) and percentage distributions of various turbulence intensities at a given altitude*

[Based upon 1947 data from Ohio thunderstorms]

Turbulence intensity	Flight altitude (feet)									
	5,000		10,000		15,000		20,000		25,000	
	N	%	N	%	N	%	N	%	N	%
Light	50	45	71	33	69	33	51	31	45	41
Moderate	45	40	91	42	82	39	59	36	29	26
Heavy	11	10	37	17	45	22	39	24	28	25
Unclassified	6	5	18	8	12	6	15	9	9	8
Total	112	100	217	100	208	100	164	100	111	100

Drafts.—Table 5 is a tabulation of all drafts[10] measured during the observational program in Florida. A few interesting features of the vertical velocity fields within a thunderstorm brought out by this table are the following:

1. The maximum values of updrafts were measured at the middle and upper levels.

2. The maximum values of downdrafts were more evenly distributed through the various altitudes.

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[10] Drafts are computed from the changes in pressure altitude of the airplane. All altitude changes during which the records indicate control by the pilot are discarded.

3. The mean updraft value was greater than the mean downdraft value at all altitudes with the exception of the 6,000-foot level, where the reverse condition prevailed.

4. Maxima of the mean updraft and downdraft values were found at the 26,000-foot level. A secondary maximum of downdraft is found at 16,000 feet. There is a striking minimum at 6,000 feet in the mean updraft value.

TABLE 5.—*Actual number of drafts measured at various altitudes during Florida operations*

[Includes only those drafts in which there was no evidence of the airplane actually climbing or diving relative to the draft itself]

Draft value (fps)	Updraft					Downdraft				
	Flight altitude (thousands of feet)					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]1	------	------	------	------
70–79.9	------	1	[1]1	1	------	------	------	------	------	------
80–89.9	------	1	------	------	------	------	------	[1]1	------	------
90–99.9	------	------	[1]1	------	------	------	------	------	------	------
Mean	17	24	24	24	25	19	18	21	17	22

[1] Subject to question.

The values indicated in table 5 do not take into account the length of time that the aircraft was in the downdraft and therefore do not indicate the amount of vertical displacement which resulted. In table 6 this is taken into consideration by using a figure obtained by multiplying the average magnitude of the draft by the distance over which it was measured.

This figure, which will be called the "displacement coefficient," when divided by the speed of the airplane, gives the altitude change which would have resulted as the aircraft flew through the draft, provided the attitude of the plane was not such as to cause a vertical translation relative to the draft.

The basic features of table 6 have been incorporated into figures 2 and 3 which also take into account the effect of various air speeds. Figure 2 indicates the maximum displacement likely to be encountered in any one draft in Florida thunderstorms and figure 3 shows the maximum displacement likely to be encountered in any one of the lower 90 percent of cases. The airplane may encounter more than one draft during one traverse.

Several features of table 6 and figure 2, which are worthy of note, are the following:

1. The maximum displacements due to the updraft increased with increasing altitude. At high altitudes an airplane flying at 150 mph would have experienced an upward displacement as great as 6,000 feet. At 6,000 feet, however, the maximum displacement expected, on the basis of the Florida data, is 1,600 feet.

TABLE 6.—*Frequency distribution of displacement coefficient at various altitudes*

[Based upon P-61C flights through Florida thunderstorms, 1946]

Displacement coefficient (1,000 ft.^{2}/sec.)	Updraft					Downdraft				
	Flight altitude (thousands of feet)					Flight altitude (thousands of feet)				
	6	11	16	21	26	6	11	16	21	26
0– 49.9	3	2	4	2	1	1	3	6	2	1
50– 99.9	17	33	42	40	20	12	26	27	14	12
100– 149.9	12	18	18	21	20	4	10	13	8	5
150– 199.9	1	12	12	11	12	2	1	5	6	8
200– 249.9	3	9	5	10	5	1	1	1	2	3
250– 299.9	1	4	9	3	5	[1]2	------	------	1	4
300– 349.9	1	1	3	3	------	------	------	[1]1	------	1
350– 399.9	------	1	[1]2	2	4	------	------	------	------	1
400– 449.9	------	1	[1]1	5	6	------	------	------	------	1
450– 499.9	------	2	2	------	1	------	------	------	------	2
500– 549.9	------	------	1	2	------	------	------	------	------	------
550– 599.9	------	1	1	1	1	------	------	------	------	------
600– 649.9	------	2	1	------	2	------	------	------	------	------
650– 699.9	------	------	1	1	1	------	------	------	------	------
700– 749.9	------	1	------	------	------	------	------	------	------	------
750– 799.9	------	------	------	1	1	------	------	------	------	------
800– 849.9	------	------	1	------	------	------	------	------	------	------
850– 899.9	------	------	------	1	1	------	------	------	------	------
900– 949.9	------	------	------	1	------	------	------	------	------	------
950–1299.9	------	------	------	------	------	------	------	------	------	------
1300–1349.9	------	------	------	------	1	------	------	------	------	------
Mean	113	168	170	186	217	116	90	98	117	179

[1] One measurement of the group subject to question.

2. Above 11,000 feet, the maximum displacement due to downdrafts increased with height but was not as great as the displacement due to updrafts at the same level. One would expect, therefore, that most airplane traverses will end at a higher altitude than they started. It is important to note that for an airplane flying at 150 mph the maximum possible downward displacement from 6,000 feet, due purely to one downdraft, was less than 1,400 feet. (In no instance was the airplane flying at the lowest level brought dangerously close to the ground by a downdraft. The pilot of the airplane flying at 5,000 feet on August 14, 1947, reported that he was carried through the base of the cloud by a strong downdraft. On this occasion, the downward motion ceased immediately after the airplane broke out of the bottom of the cloud.)

3. At all levels, except the 6,000-foot level, the mean upward displacement was greater than the mean downward displacement.

Weather Within the Thunderstorm

The weather conditions that an airplane will most likely encounter in thunderstorm flying can be determined from the occurrences of weather phenomena that were encountered by Project airplanes during their traverses through thunderstorms. This weather was reported by members of the air crews. As has been pointed out earlier, a weather observer was added to each crew for the Ohio flights; therefore, the Ohio data should be more complete than that from Florida. As operations progressed, the crews became accustomed to the conditions encountered within thunderstorms and it is likely that the intensity of the weather elements, as reported, decreased continually through the two seasons of operation. In spite of these reasons for the data not being strictly comparable, they must be used, since they represent the only source of information regarding the distribution and magnitude of the weather elements within the storms. The rotation of assigned flight altitudes among the various crews precluded the preponderance of a single man's judgment at any one level.

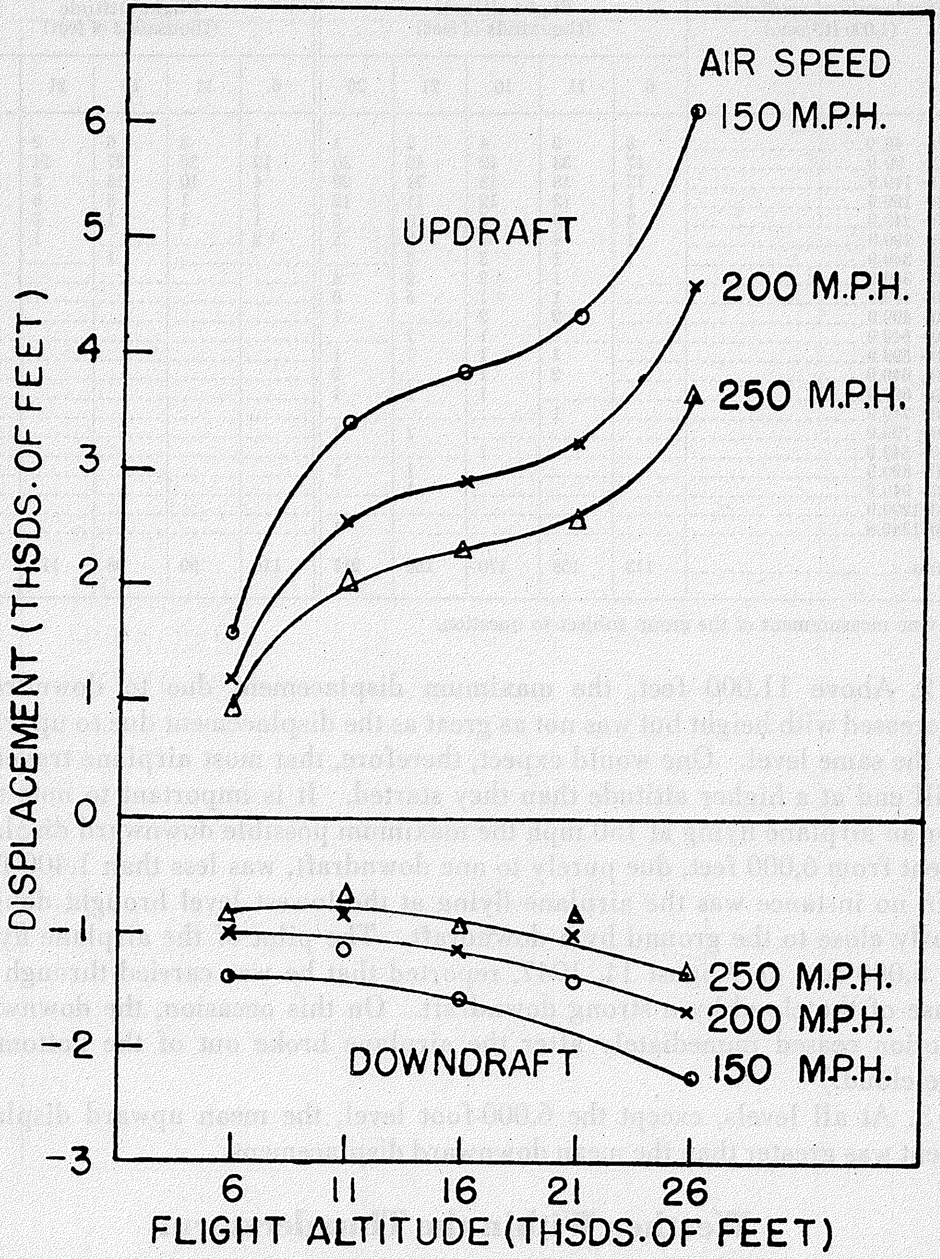

Figure 2.—Maximum displacement that could be produced by any one draft experienced in Florida thunderstorms. The three curves show the displacement variations with air speed.

Rain.—In discussing the aerial observations of rain, it must be considered that the phenomenon actually reported is the occurrence of liquid water.

This water may be falling to the ground, and would therefore be rain in the truest sense, or it may be suspended in, or ascending with, the rising currents.

Other thunderstorm analysis shows that rain, as measured at the surface, is closely associated with the downdraft. However, an airplane will frequently encounter high-water concentrations in an area of updraft where the upward motion prevents any of the water from falling out. It is found that rain was encountered on almost every traverse at altitudes below the freezing level. The fact that "no rain" was reported more frequently at the lower levels in Ohio than in Florida is due, at least in part, to the fact that in Ohio a greater

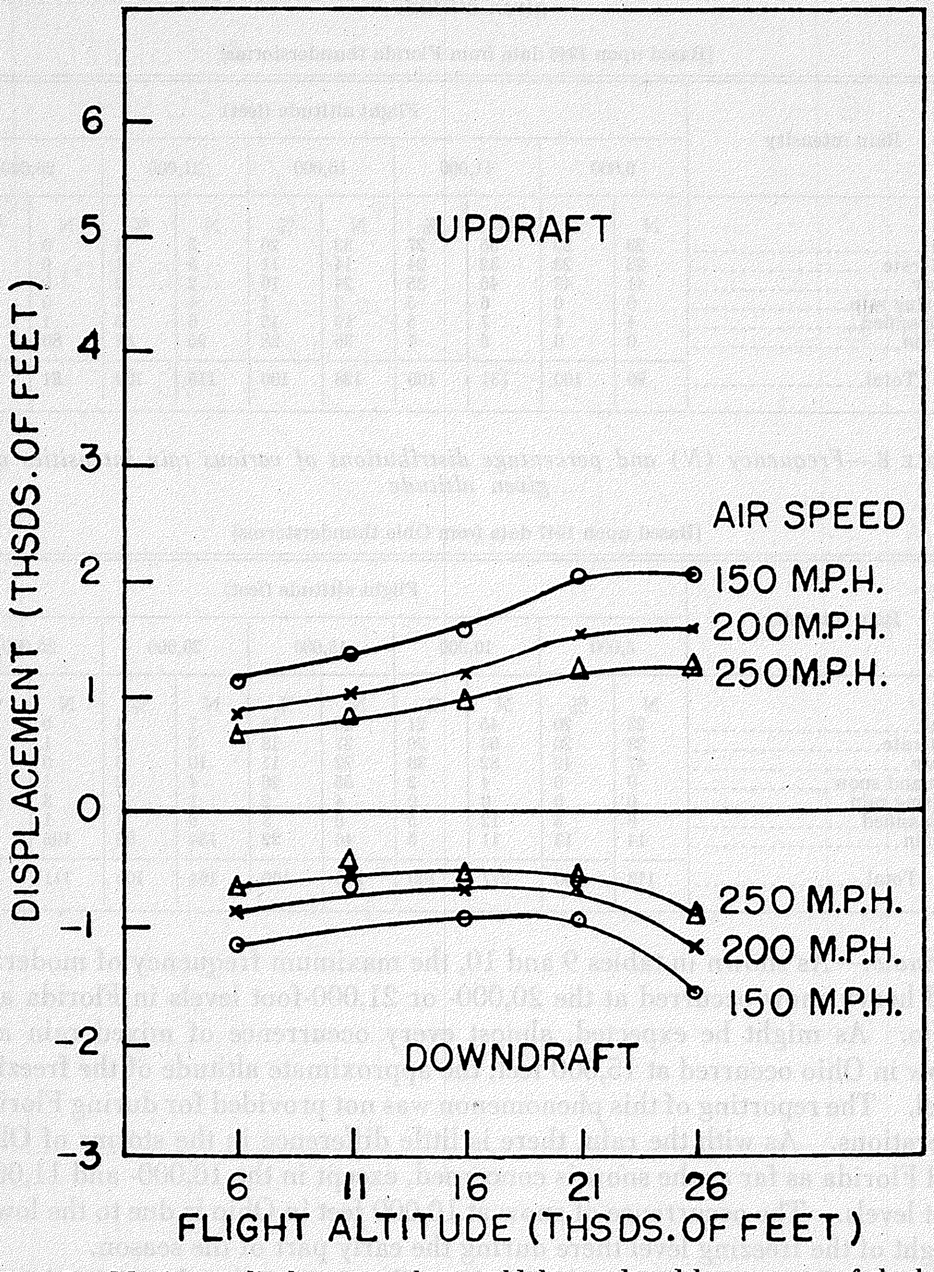

Figure 3.—Maximum displacement that could be produced by any one of the lower 90 percent of the drafts experienced in Florida thunderstorms. The three curves show the displacement variations with air speed.

percentage of measurements were made in cumulus clouds from which, in many cases, rain had not yet begun to fall. The frequency distribution of the various intensities of rain at a given altitude is shown in tables 7 and 8.

TABLE 7.—*Frequency (N) and percentage distributions of various rain intensities at a given altitude*

[Based upon 1946 data from Florida thunderstorms]

Rain intensity	Flight altitude (feet)									
	6,000		11,000		16,000		21,000		26,000	
	N	%	N	%	N	%	N	%	N	%
Light	29	30	35	27	33	26	3	3	0	0
Moderate	22	23	32	24	14	11	5	4	0	0
Heavy	41	43	46	35	24	19	2	2	0	0
Freezing rain	0	0	6	5	2	1	4	3	0	0
Unclassified	4	4	7	5	19	15	6	5	1	1
No rain	0	0	5	4	36	28	95	83	80	99
Total	96	100	131	100	128	100	115	100	81	100

TABLE 8.—*Frequency (N) and percentage distributions of various rain intensities at a given altitude*

[Based upon 1947 data from Ohio thunderstorms]

Rain intensity	Flight altitude (feet)									
	5,000		10,000		15,000		20,000		25,000	
	N	%	N	%	N	%	N	%	N	%
Light	23	20	45	21	38	18	7	4	0	0
Moderate	23	20	63	29	37	18	3	2	1	1
Heavy	47	42	82	38	22	11	10	6	0	0
Rain and snow	0	0	4	2	55	26	4	2	1	1
Freezing rain	0	0	0	0	4	2	1	1	3	2
Unclassified	6	5	12	5	6	3	5	3	1	1
No rain	14	13	11	5	46	22	134	82	105	95
Total	113	100	217	100	208	100	164	100	111	100

Snow.—As shown in tables 9 and 10, the maximum frequency of moderate and heavy snow occurred at the 20,000- or 21,000-foot levels in Florida and Ohio. As might be expected, almost every occurrence of mixed rain and snow in Ohio occurred at 15,000 feet, the approximate altitude of the freezing level. The reporting of this phenomenon was not provided for during Florida operations. As with the rain, there is little difference in the storms of Ohio and Florida as far as the snow is concerned, except in the 10,000- and 11,000-foot levels. The occurrence of snow at 10,000 feet in Ohio is due to the lower height of the freezing level there during the early part of the season.

Icing.—Of more concern than rain and snow in the determination of flight hazards in thunderstorm traverses is the occurrence of icing. In those storms flown by the Thunderstorm Project, ice was encountered on more than one-half of all traverses at the 20,000-foot level, as can be seen from tables 11 and 12.

The data of both seasons indicate that an overwhelming majority of all cases of icing were classified by the air crews as rime. In the two seasons of flying there was no occasion of ice accumulating on the P–61C's to a

Table 9.—*Frequency (N) and percentage distributions of various snow intensities at a given altitude*

[Based upon 1947 data from Florida thunderstorms]

Snow intensity	Flight altitude (feet)									
	6,000		11,000		16,000		21,000		26,000	
	N	%	N	%	N	%	N	%	N	%
Light	0	0	0	0	42	33	41	36	29	36
Moderate	0	0	0	0	23	18	28	24	11	13
Heavy	0	0	0	0	10	8	25	22	15	19
Unclassified	1	1	0	0	12	9	9	8	18	22
No snow	95	99	131	100	41	32	12	10	8	10
Total	96	100	131	100	128	100	115	100	81	100

Table 10.—*Frequency (N) and percentage distributions of various snow intensities at a given altitude*

[Based upon 1947 data from Ohio thunderstorms]

Snow intensity	Flight altitude (feet)									
	5,000		10,000		15,000		20,000		25,000	
	N	%	N	%	N	%	N	%	N	%
Light	0	0	13	6	50	24	58	35	45	40
Moderate	0	0	5	2	33	16	41	25	24	22
Heavy	0	0	0	0	13	6	37	23	24	22
Rain and snow	0	0	4	2	55	27	4	2	1	1
Unclassified	2	2	11	5	13	6	5	3	7	6
No snow	110	98	184	85	44	21	19	12	10	9
Total	112	100	217	100	208	100	164	100	111	100

Table 11.—*Frequency (N) and percentage distributions of various icing intensities at a given altitude*

[Based upon 1946 data from Florida thunderstorms]

Icing intensity	Flight altitude (feet)									
	6,000		11,000		16,000		21,000		26,000	
	N	%	N	%	N	%	N	%	N	%
Light	0	0	5	4	34	27	42	36	22	27
Moderate	0	0	0	0	1	1	26	23	5	6
Heavy	0	0	0	0	1	1	8	7	5	6
No icing	96	100	126	96	92	71	39	34	49	61
Total	96	100	131	100	128	100	115	100	81	100

Table 12.—*Frequency (N) and percentage distributions of various icing intensities at a given altitude*

[Based upon 1947 data from Ohio thunderstorms]

Icing intensity	Flight altitude (feet)									
	5,000		10,000		15,000		20,000		25,000	
	N	%	N	%	N	%	N	%	N	%
Light rime	0	0	5	2	35	17	38	23	23	21
Moderate rime	0	0	0	0	1	1	14	8	8	7
Heavy rime	0	0	0	0	0	0	3	2	5	5
Rime and clear	0	0	0	0	3	1	10	6	1	1
Clear	0	0	1	1	2	1	5	3	2	2
Unclassified	0	0	6	3	18	8	24	15	15	13
No icing	112	100	205	94	149	72	70	43	57	51
Total	112	100	217	100	208	100	164	100	111	100

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degree that safe flight was not possible. The most probable reason for this is the relatively short period of time that the airplanes were subjected to the icing conditions. In this regard it should be pointed out that on July 22, 1946, a Project sailplane, spiraling upward in an updraft region of a thunderstorm, iced so heavily that the pilot lost the use of the elevator control surfaces. In this instance the sailplane had been in the cloud above the altitude of the clear air freezing level about 12 minutes before the ice accretion reached such proportions.

In almost every instance the ice evaporated between traverses while the airplane flew in the clear air.

Hail.—As can be seen from tables 13 and 14 relatively few instances of hail were noted in either the Florida or the Ohio thunderstorms. However, the records indicate that a decided maximum of the hail was observed in the middle levels. It appears as if the region of hail in any storm and the duration of hail in that region are relatively small. Therefore, it is likely that an airplane will not encounter hail even though it may be in the storm. This is borne out by the fact that when hail was present it was found on only 25 percent or less of the traverses through the storm at the level of its occurrence. Very seldom was it found at more than one or two levels in the same storm.

TABLE 13.—*Frequency (N) and percentage distributions of various hail intensities at a given altitude*

[Based upon 1946 data from Florida thunderstorms]

Hail intensity	Flight altitude (feet)									
	6,000		11,000		16,000		21,000		26,000	
	N	%	N	%	N	%	N	%	N	%
Light	0	0	1	1	4	3	1	1	2	3
Moderate	0	0	1	1	6	4	3	3	0	0
Heavy	0	0	1	1	3	3	0	0	0	0
No hail	96	100	128	97	115	90	111	96	79	97
Total	96	100	131	100	128	100	115	100	81	100

TABLE 14.—*Frequency (N) and percentage distributions of various hail intensities at a given altitude*

[Based upon 1947 data from Ohio thunderstorms]

Hail intensity	Flight altitude (feet)									
	5,000		10,000		15,000		20,000		25,000	
	N	%	N	%	N	%	N	%	N	%
Light	1	1	9	4	0	0	5	3	2	2
Moderate	0	0	2	1	2	1	3	2	0	0
Heavy	0	0	5	2	4	2	0	0	0	0
Unclassified	1	1	10	5	4	2	2	1	1	1
No hail	110	98	191	88	198	95	154	94	108	97
Total	112	100	217	100	208	100	164	100	111	100

In spite of its relative infrequency there is evidence that hail, when present, can do considerable damage to an airplane. It should be borne in mind that the regions of operations of the Thunderstorm Project were considerably removed from the region of maximum occurrence of hail at the surface (ref. 12).

Interrelation of turbulence and precipitation.—Many of the older manuals of instruction for thunderstorm flying have indicated that areas of minimum turbulence should correspond to areas of heavy rain because of a stabilizing effect due to the weight of the rain.

Data from the two seasons of operation indicate that this is not true. Actually the opposite seems to occur more frequently. To illustrate this point, simultaneous occurrences of various intensities of precipitation and of turbulence, based on air-crew opinion, from the 1947 data have been compiled in table 15. It is clearly evident that the intensity of turbulence in most cases varies directly with the intensity of precipitation. This relation most probably indicates that most of the rain and snow encountered in a thunderstorm is actually held aloft by drafts.

TABLE 15.—*Relationship between simultaneous occurrences of various intensities of precipitation and turbulence*

[Based upon 1947 data from Ohio thunderstorms]

Turbulence intensity	Precipitation intensity					
	Rain			Snow		
	Light	Moderate	Heavy	Light	Moderate	Heavy
Light	310	111	39	335	75	14
Moderate	87	104	101	87	101	37
Heavy	18	19	53	19	23	54
None	48	15	13	39	5	2

The reporting system used in Florida makes it impossible to obtain data on the simultaneous occurrence of the various intensities of turbulence and precipitation. However, the maximum intensity of turbulence and precipitation that occurred on every traverse (although they may not have occurred together) is known. Table 16 shows such data for Florida storms flown in 1946.

TABLE 16.—*Relationship between the maximum intensity of precipitation and maximum intensity of turbulence that occurred on the same traverse*

[Based upon 1946 data from Florida thunderstorms]

Turbulence intensity	Precipitation intensity					
	Rain			Snow		
	Light	Moderate	Heavy	Light	Moderate	Heavy
Light	81	44	40	83	20	9
Moderate	23	30	41	23	31	14
Heavy	16	24	46	20	20	30
None	16	9	7	11	7	1

Lightning strikes.—During the two seasons of operations the airplanes were struck by lightning 21 times according to pilot reports and subsequent ground inspection. In general the damage was limited to a group of small holes in the airplane skin. On one occasion, however, lightning struck the pitot tube, and the pilot reported a momentary air-speed indication of 600 mph. Ground inspection revealed that the pitot tube had been bent a few degrees from normal. It is interesting to note that no complete radio failure can be attributed to the effect of lightning. The number of reported strikes at the various altitudes for both Florida and Ohio is shown in table 17.

TABLE 17.—*Frequency distribution of lightning strikes by flight altitude and operating season*

[Based upon reports from aircrews after flights through thunderstorms]

Flight altitude	Number of lightning strikes	
	1946	1947
6,000	1	0
11,000	0	1
16,000	4	5
21,000	1	1
26,000	4	4

The First Gust

The hazard to aircraft in take-off and landing, due to unexpected wind changes during thunderstorm conditions, is well recognized. According to an analysis by the Civil Aeronautics Administration, during the years 1938 to 1945 there were 56 accidents involving commercial or private aircraft attributed to thunderstorms, of which 10 (18 percent) appear to have been caused by such wind changes. The following are descriptions furnished by the CAA of some of the accidents, during thunderstorms, apparently due to this cause:

1. *Middle Atlantic States, 1938.*

While on a cross-country flight, pilot encountered a severe electrical storm. Unable to maneuver the plane in turbulent air, he attempted a landing on a small farm field. A gust of wind struck the plane as he was about to land. The plane hit the ground on the nose and the left wing was demolished.

2. *New England States, 1944.*

Pilot lost control while landing in thunderstorm and was blown across the airport and turned over.

3. *Great Lakes region, 1945.*

In approaching the airport, the pilot observed a thunderstorm to the northwest. He circled once at an altitude of 500 feet to ascertain the extent of the turbulence and then started the landing approach, in which heavy rain was encountered at an altitude of 200 feet, but which did not obscure the runway. As the wheels contacted the surface at the middle of the 2,900-foot runway, a severe 180° wind shift occurred, causing the airliner to veer off of the runway onto wet sod. The captain was unable to stop by braking or ground looping, and the aircraft crossed the airport border, hit a telephone pole, and came to rest in a drainage ditch adjacent and parallel to a railroad track. Contributing factors to the accident were the pilot's decision to land before the storm broke, and unnecessarily high and fast approach to land.

Since these unexpected shifts in the wind can be so hazardous, the Thunderstorm Project has undertaken a detailed investigation of their nature, their probability of occurrence, and the determination of methods of forecasting the changes of direction. The problem of forecasting the magnitude of the increase in speed is also being attacked, but results at present are too indefinite for inclusion here. Data for a detailed analysis of the marked changes in wind direction and speed accompanying thunderstorms were obtained from a network of 55 autographic meteorological stations near Orlando, Fla., in the spring and summer of 1946, and 62 stations near Wilmington, Ohio, in the spring and summer of 1947.

Origin of the wind shift.—When the cold downdraft of a mature thunderstorm cell reaches the surface of the earth it spreads out in all directions. In cases where the cell is moving with respect to the earth, the horizontal velocity of the cell is added to the velocity of the spreading colder air with the result that the highest velocities are observed at the leading edge and the lowest velocities are found at the trailing edge of the thunderstorm cell. The resultant velocity of this cold air is much higher than that of the warmer air it displaces, so that upon its arrival at a given station the wind speed usually rises markedly within a few seconds. Wind speeds exceeding 60 miles per hour have been observed over the Ohio network during thunderstorms. The sharp increase in wind speed, associated with the boundary between the cold air originating in the downdraft and the warmer air ahead, has been termed the "first gust" since it often appears as the first major gust of a period of high gusty winds. The amount of change in wind direction associated with the first gust depends on the direction prevailing previously, the position of the station with respect to the cell, and the direction of movement of the cell iself; changes of as much as 180 degrees have been observed.

Caution period.—For this study the period following the first gust, during which the mean wind speed over any consecutive 5-minute interval is greater than 10 miles per hour, has been defined as the "caution period." The duration of the caution period at 52 stations has been studied for each of 20 Ohio storms. Based on this sample, one may say that gustiness and relatively high wind speeds will persist for an average of 17 minutes after the occurrence of the first gust; however, the gustiness can end within 2 or 3 minutes or can last as long as 90 minutes. Figure 4 indicates that the duration of the caution period is less than 12 minutes in 50 percent of the cases and greater than 46 minutes in only 10 percent of the cases.

First-gust velocities.—With the arrival of the cold air from the downdraft, the surface wind speed increases from 4 or 5 miles per hour to an average of 18 miles per hour in a few seconds. The first-gust intensity observed will depend on both the age of the storm and the position of the observer with respect to it. As seen from figure 5, more than half of the observations show a first-gust wind speed greater than 16 miles per hour, but less than 5 percent indicate wind speeds exceeding 30 miles per hour. In one Ohio storm, not selected for this study, a first gust of 62 miles per hour was recorded.

The average change in wind direction associated with the first gust is 39 degrees; however, wind shifts of more than 90 degrees occurred 12 percent of the time.

Absolute peak wind speed of the caution period.—About 43 percent of the time the wind speed of the first gust is the highest wind speed which will be measured during the entire caution period. A cumulative percentage distribution of the absolute peak wind speed is included in figure 5. On the average the absolute peak wind speed exceeds the first-gust wind speed by 2 miles per hour and occurs 4.4 minutes later. The direction of the absolute peak wind speed is the same as that of the first gust 74 percent of the time and within 10 degrees 87 percent of the time.

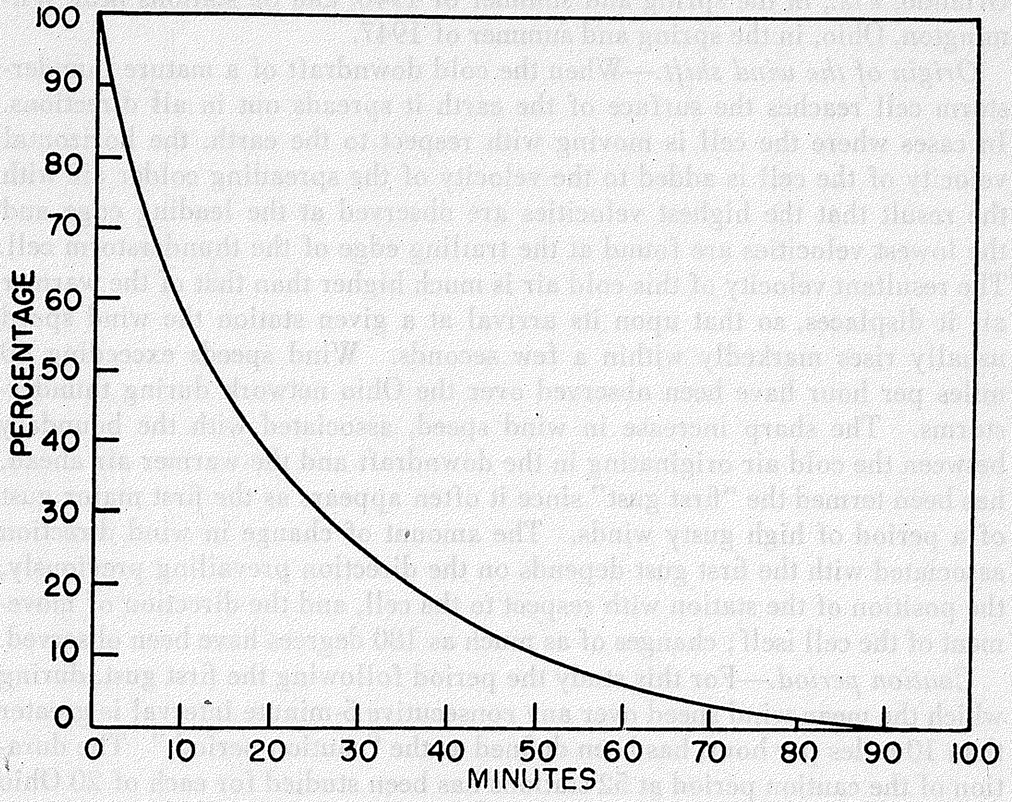

Figure 4.—Cumulative percentage distribution of length of caution period, showing percentage of cases equal to or greater than a stated duration.

Effective first-gust velocity.—Another significant wind parameter from a pilot's standpoint is the "effective first-gust velocity" which is essentially the effect of the first gust along the longitudinal axis of an airplane heading into the previously prevailing wind.

As may be seen in figures 6 and 7, the effective first-gust velocity is the difference between the component of the first gust along the previously prevailing wind direction and this wind velocity.

When the direction of the first gust is at right angles to the previously prevailing wind, the effective first-gust velocity is equal to the prevailing wind velocity but is opposite in sign. In all cases where the prevailing wind was less than 5 miles per hour, an effective first-gust velocity was not calculated, since, under such conditions, the runway used is usually not dictated by the wind direction. Figure 8 shows how the effective first-gust velocity is distributed. Negative velocities indicate the loss in air speed and positive values the increase in air speed due to the effective first gust. It is interesting to note that in approximately 38 percent of the measurements, the positive effective first-gust velocity exceeded 10 miles per hour while in only 1 percent of the measurements did the negative values exceed 10 miles per hour.

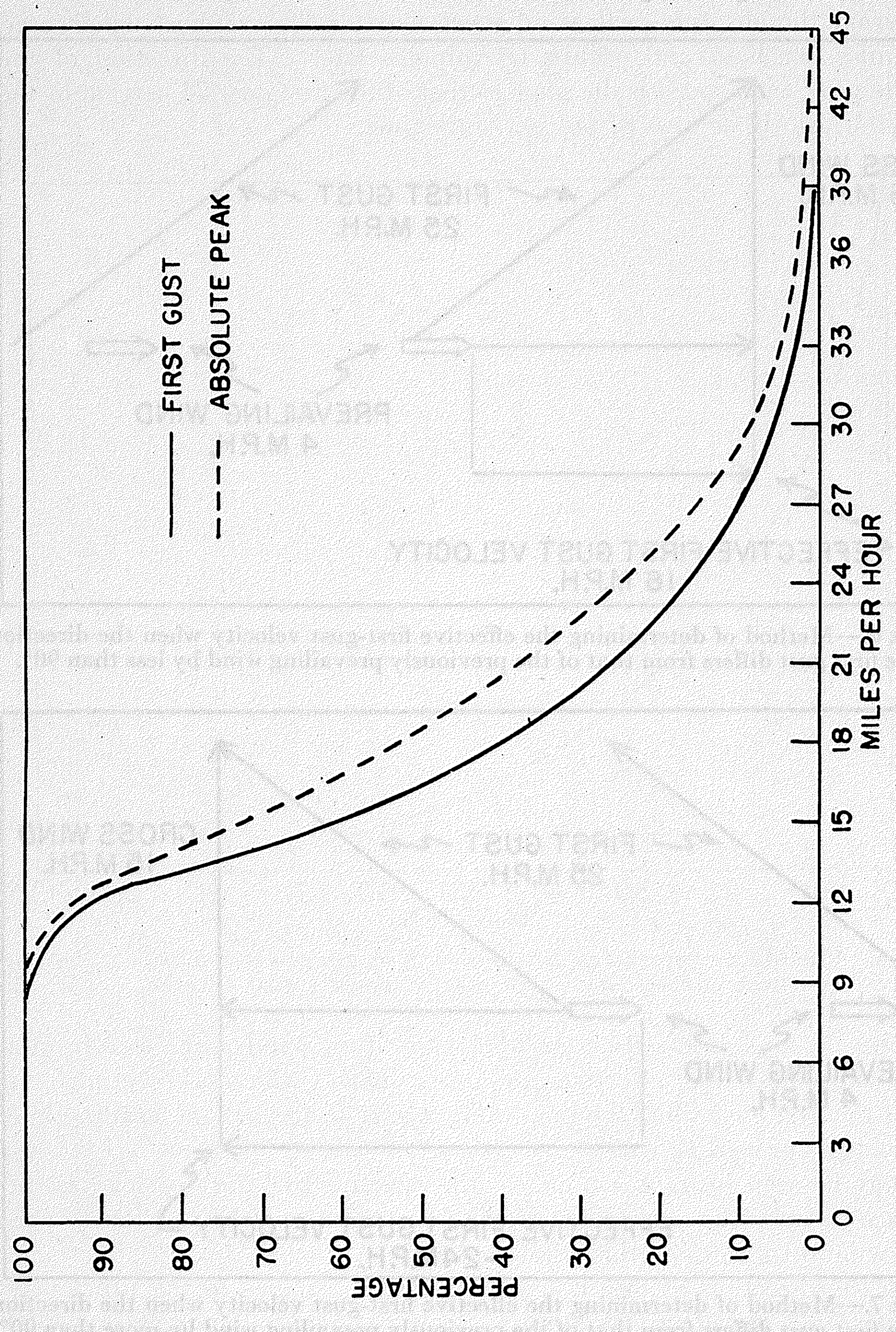

FIGURE 5.—Cumulative percentage distribution of first-gust and absolute-peak velocities equal to or greater than a stated amount.

The rate of progression of the first-gust line as observed on the ground is about 18 miles per hour; however, over small areas the speed of movement of this wind discontinuity sometimes accelerates, with the result that it can travel as fast as 60 miles per hour. If the effective first gust were to overtake an airplane in take-off, it would act as a sudden tailwind, resulting in a loss of air speed, thereby requiring a greater length of runway than anticipated. The effective first gust would act as a sudden headwind if the airplane were taking off towards it.

In landing, the sudden loss in air speed due to having been overtaken by the effective first gust might cause sudden loss of altitude, whereas the effective first gust, acting as a sudden increase in heading, could cause overshooting or "ballooning."

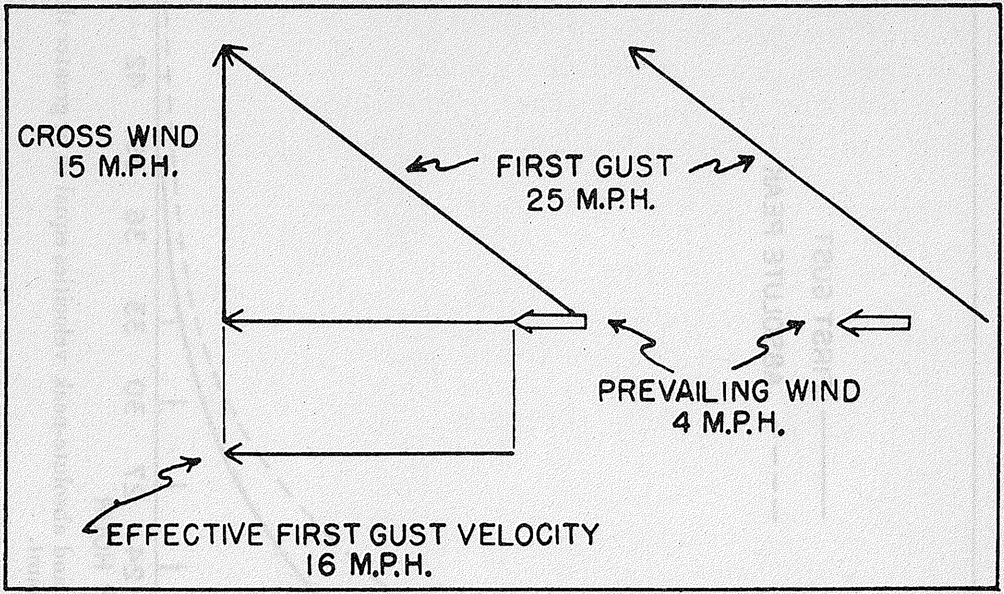

FIGURE 6.—Method of determining the effective first-gust velocity when the direction of the first gust differs from that of the previously prevailing wind by less than 90°.

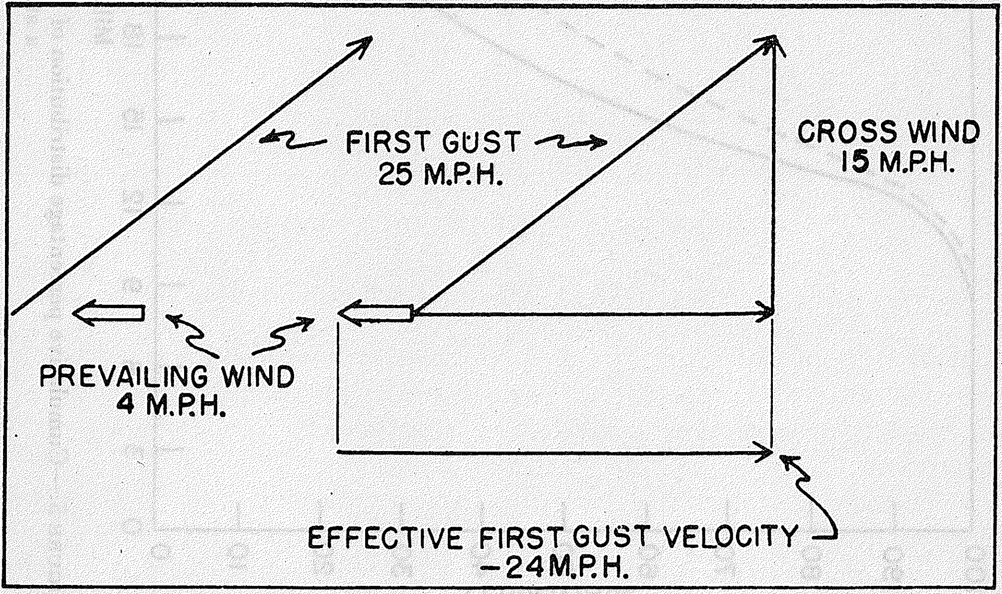

FIGURE 7.—Method of determining the effective first-gust velocity when the direction of the first gust differs from that of the previously prevailing wind by more than 90°.

Usually the direction of the high wind speeds coincides with the direction of movement of the first-gust line; however, in a small percentage of the cases, the difference may be appreciable—as much as 90 degrees. In such cases the direction of the high winds could be along a runway but the line of wind-speed discontinuity could move at right angles to it.

Aids in forecasting the direction of the first gust.—Although it is at present impossible to set down rules for forecasting the wind direction associated with the first gust in all cases, there are conditions under which reasonable, short-period forecasts can be made.

The first gust and thundercloud radar echoes, as observed on a plan-position-indicator (PPI), are related. This is not surprising since the radar echoes are reflections of liquid or solid water particles and the cold downdraft from which the first gust originates is essentially caused by the precipitation (refs. 9 and 10). In no case has a first gust been observed without the presence of an associated echo on the PPI 'scope of the control radar used.

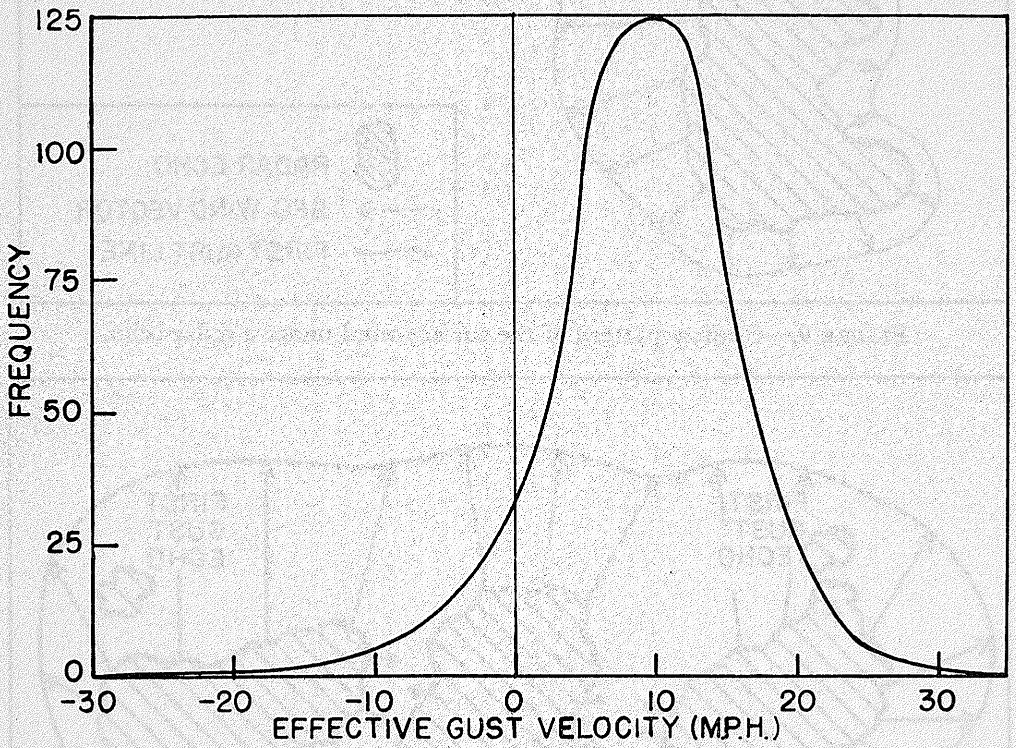

FIGURE 8.—Frequency distribution of the effective first-gust velocity. Negative velocities indicate decrease of air-speed; positive values indicate gain of air speed.

From the data gathered by the Thunderstorm Project, both in Ohio and Florida, it can be seen that the wind immediately behind the first gust blows out in all directions from the radar echo. Since the first gust velocity depends on both the radar echo movement and the prevailing wind velocity, it will be greatest at the leading edge of the echo and least or even undetectable at the trailing edge. A schematic picture of this outflow pattern is shown in figure 9.

When two or more echoes form a line, the first gust at the leading edge is also substantially stronger than that at the trailing edge for the above reasons. In the areas between echoes, there can be a diminution of the wind outflow due to mutual interaction; however, if a rapidly developing echo is adjacent to a dissipating one, the outflow from the former will predominate, as is shown in figure 10.

The first gust from a line of echoes is actually the resultant of the effects of each of the component echoes. Consequently, the general direction of the first-gust movement will be outward from and at approximately right angles to the line of cells. However, at the ends of the echo line, the first-gust movement is outward and parallel to the line.

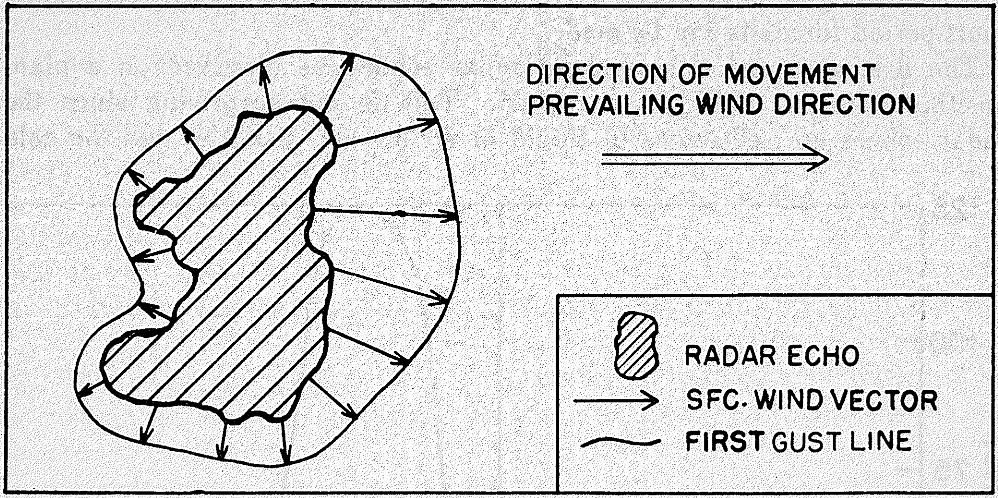

FIGURE 9.—Outflow pattern of the surface wind under a radar echo.

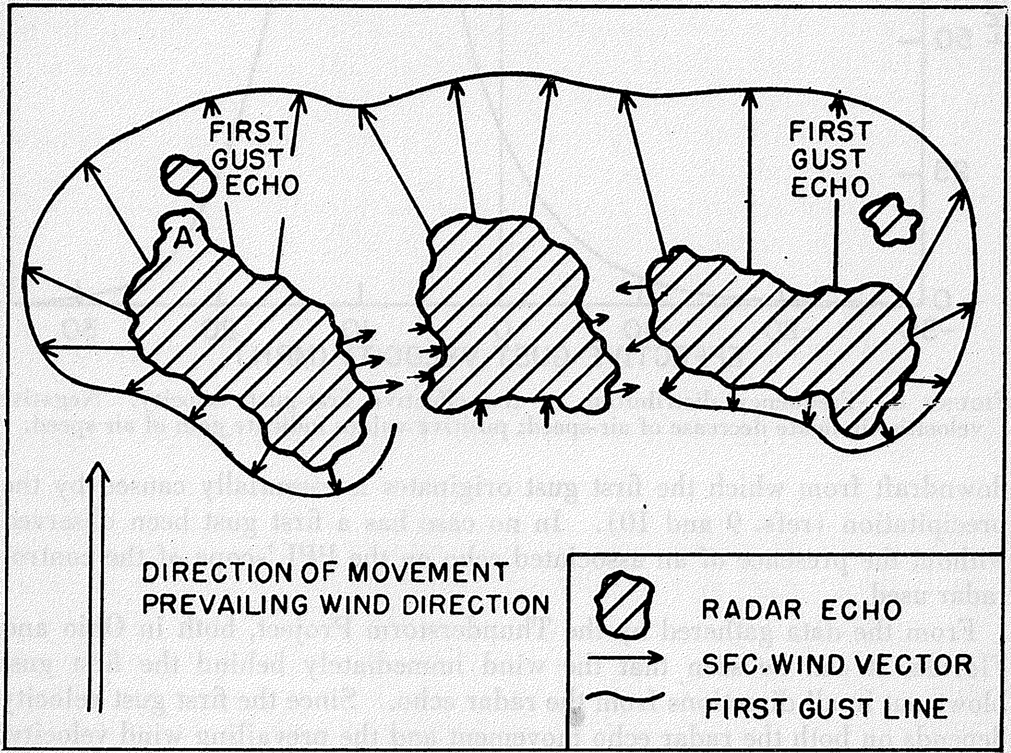

FIGURE 10.—Outflow pattern of the surface wind under a line of radar echoes.

As the cold, fast-moving air associated with the downdraft underruns the warmer air ahead, it appears to "trigger" the development of new radar echoes. They are labeled "first-gust echoes" in figure 10. The appearance of such echoes usually indicates both the presence and direction of movement of the first gust. After several minutes the first-gust echo frequently coalesces with the "parent" echo to form an amoeboid projection such as "A" in figure 10.

The first gust appears initially within 1 or 2 miles of the radar echo, but as the storm ages, it can run out as much as 11 or 12 miles ahead of the echo edge. Frequently, however, the first gust echoes develop before the separation between the first gust and the radar echo edge becomes as large as this. In a dissipating storm, of course, the first gust moves out ahead and disappears without additional cell development.

The preceding discussion, based on a study of seven Florida and five Ohio storms, makes possible the following general statements which may be used as aids in predicting the approximate direction of movement of the first-gust line and direction of the first gust:

1. The winds behind the first-gust line blow out from the radar echo. If an echo within 10 or 15 miles of a station is observed to be moving or propagating directly toward it, the first gust is likely to arrive at the station and have the same direction as the direction of movement or propagation.
2. If new first-gust echoes appear, the first-gust line has probably passed beyond them.
3. If a line of echoes is moving toward a station, in a majority of the cases, the first gust will be from a direction at right angles to the line or in the direction of movement of the line.
4. If an echo or line of echoes is moving away from a station, it is probable that no first gust will occur.
5. The first-gust forecasts cannot be made in the following cases:
    - *a.* When numerous small echoes surround the station.
    - *b.* When two or more lines of echoes approach the station from different directions.
    - *c.* When the echoes show no apparent movement or propagation.

Altimeter Errors Due to Surface Pressure Changes During Thunderstorms

During a thunderstorm, rapid surface-pressure variations can occur. Frequently the pressure rises rapidly, stays high for several minutes, and then returns to its previous value; occasionally it first falls and then returns to its pre-thunderstorm value. In a majority of cases these pressure changes occur within a 10- to 15-minute interval. A study of the magnitude of the pressure changes occurring during the Ohio operations was made to see whether they were sufficiently great to be hazardous.

For each of the days on which one or more thunderstorms occurred, the maximum pressure rise and fall were converted to the equivalent altimeter error and tabulated.

From tables 18 and 19 it can be seen that in 22 percent of the cases, if a pilot landed during the maximum pressure, using an altimeter setting given to him only 10 or 15 minutes earlier, his altimeter would indicate that he was 60 feet or more below the true altitude. Of greater concern to the pilot are pressure altitude readings which are too high. If a pilot used an altimeter setting given to him during the maximum pressure and landed after the pressure had fallen, on 26 percent of the days he would have found that his altimeter still read 60 feet or more above the true altitude after he was on the ground. On two occasions the altimeter would have read over 140 feet above the true altitude when he landed.

Table 18.—*Altimeter indication lower than true altitude due to pressure rise*

	Number of feet in error					
	0-19	20-39	40-59	60-79	80-99	100 and over
Number of cases	18	14	6	6	5	0
Percentage of cases	37	29	12	12	10	0

Table 19.—*Altimeter indication higher than true altitude due to pressure rise*

	Number of feet in error					
	0-19	20-39	40-59	60-79	80-99	100 and over
Number of cases	25	11	5	3	3	2
Percentage of cases	51	23	10	6	6	4

The largest surface-pressure increases occur during periods of heavy thunderstorm rain. It should be realized, therefore, that the altimeter setting given out at such times will soon be in error. Similarly, one must be aware of the fact that during heavy thunderstorm rain the surface pressure has probably risen sharply in the previous 10 or 15 minutes with the result that the altimeter in the aircraft can be seriously in error if it is not corrected. Since the visibility is markedly reduced during periods of heavy rainfall when the pressure is most likely to change, the importance of using a correct altimeter setting becomes more evident.

Forecasting Turbulence In Thunderstorms by Means of Atmospheric Soundings

This study was made to test the assumption that the turbulence during thunderstorms, as indicated by such quantities as the maximum effective gust velocity ($|U_e|_{max.}$) or the frequency of gusts, is related to the density difference between the air rising within the thundercloud and the air outside. The turbulence measurements obtained by the P–61C airplanes during Thunderstorm Project operations were correlated with thermodynamic parameters obtained from radiosonde and rawinsonde observations. The soundings used were the ones made by the Thunderstorm Project supplemented by those available on the normal teletype circuit. A total of 28 days, 16 in Florida and 12 in Ohio, were chosen for this investigation. On each of these days airplane flights through thunderstorms were made at a minimum of 3 levels including the 11,000- or 16,000-foot level or both.

The thermodynamic parameter.—After testing several thermodynamic parameters indicating the density difference between the air inside and outside the thundercloud, it was found that the temperature difference (ΔT), suggested by J. J. George (ref. 13) and others, is the most effective for forecasting turbulence. The following is the definition of ΔT as given by George:

> The cloud base or condensation level was determined and the moist adiabat was drawn through the original sounding curve at the condensation level. The difference in temperature measured along constant pressure between the two curves was taken at the maximum point of separation of the two curves or the level at which the humidity dropped below 50 percent (other than shallow dry layers), whichever was the lower.

His complete instructions for calculating ΔT are given in the appendix. In this study the $\triangle T$ was determined for only the first 400 mb. of the sounding.

The turbulence parameter.—The following turbulence parameters based on the Thunderstorm Project data were correlated with ΔT:

1. The maximum effective gust velocity: The quantity used was the absolute maximum effective gust velocity measured on any given day.
2. Distribution of gusts:
   - a. Florida data: The average number of feet traversed per measurable gust.
   - b. Ohio data: The average number of seconds traversed per measurable gust.

Because of the difference in the manner of tabulating the gust data for 1946 as compared with that in 1947, the turbulence parameters for Florida were in terms of length of traverse per gust and for Ohio the number of seconds per gust. Due to variation of air speed with density, the data for the two seasons are not directly comparable.

Analysis and results.—A scatter diagram showing the relationship between $|U_e|_{max.}$ and $\triangle T$, using both the Florida and Ohio data is shown in figure 11. It is evident that there is a correlation between these variables, the correlation coefficient being 0.64. The correlation coefficients are 0.64 for the Florida and 0.68 for the Ohio data. Although the samples used were relatively small, these correlation coefficients are fairly significant. Analysis was made of the relationship between ΔT and the distribution of gusts. The correlation coefficients obtained were too small to be considered significant for the limited number of cases used in this study. Similarly the existence of a significant relationship between $|U_e|_{max.}$ and the distribution of gusts could not be established.

It may be concluded, however, that the thermodynamic parameter, ΔT, can be of use in forecasting $|U_e|_{max.}$ which can be considered a measure of turbulence. This study confirms the conclusions reached by George in his study of the relationship between ΔT and the turbulence measured by the XC–35 airplane during flight investigations of the NACA (ref. 14).

Technique Used in Piloting Thunderstorm Project Airplanes

The piloting technique used on Thunderstorm Project flights was adopted for purely scientific reasons. However, it was a method already in practical use by some air lines and advocated by the Air Force (ref. 15). The P–61C pilots made 1,363 traverses through thunderstorms without mishap. The flight technique, therefore, may be of general interest.

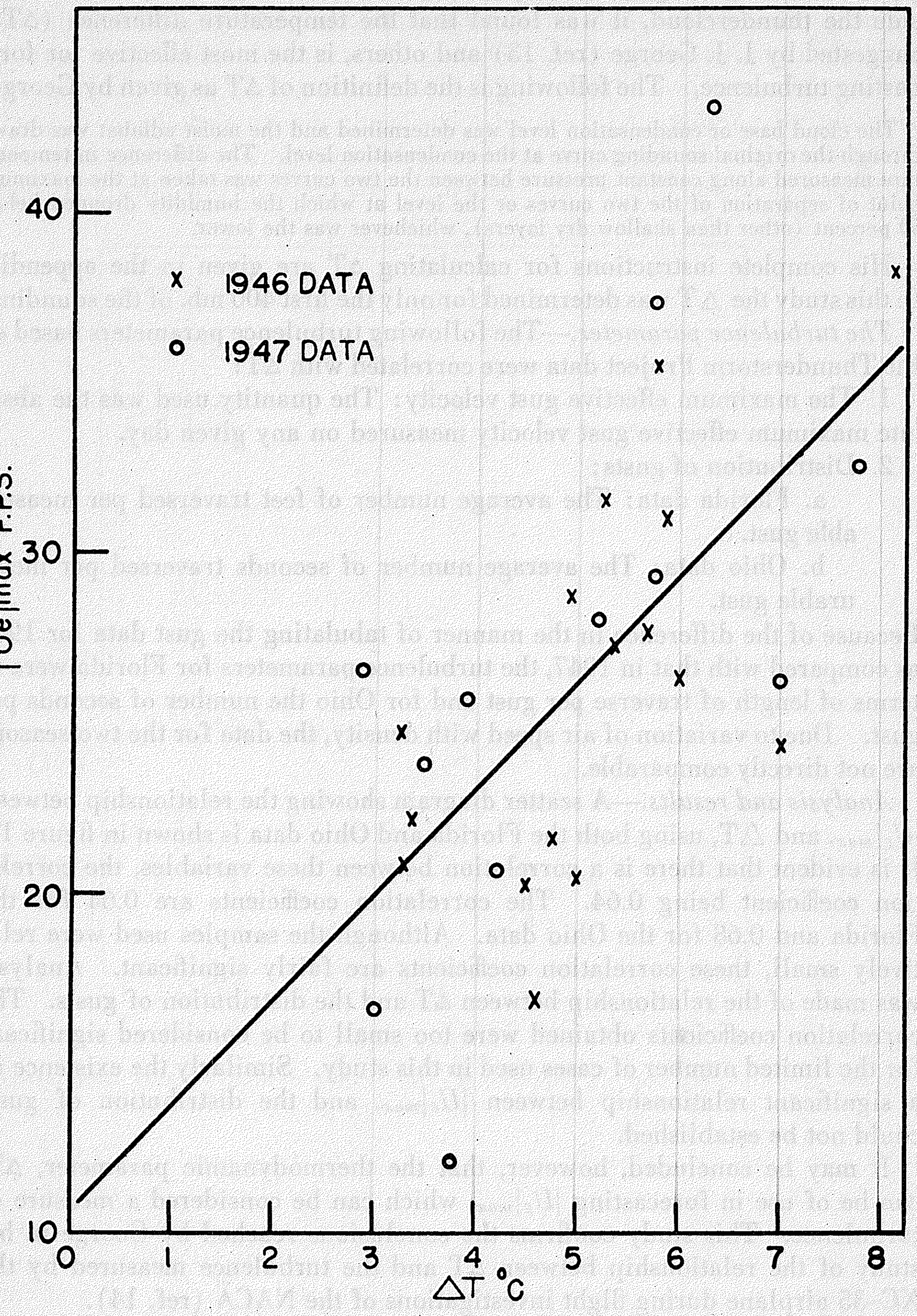

Figure 11.—Relationship between the maximum effective gust velocity, $[U_e]max.$ and Δ T (26 cases). Regression line: $[U_e]max.=3.1\ \Delta\ T+10.6$.

Gust and draft velocities were calculated from measurements of accelerations induced on the airplanes and of changes of the pressure altitude of the airplanes. Since control by the pilot also induces accelerations and produces changes in altitude, it was necessary that thunderstorm traverses be made with a minimum of pilot control. All movements of the controls were automatically recorded and when, for reasons of safety, the pilot deemed it necessary to exercise control, that portion of the record containing pilot-induced changes was eliminated. Therefore, in order to obtain valid records, the technique of traversing the storm consisted of trimming the airplane for straight and level flight at slow-cruise air speed[11] and allowing it to ride out all angular and linear displacements due to turbulence except in cases where the displacement reached serious proportions. This technique worked well using the P–61C which is fundamentally a sturdy airplane although, consistent with its design as a fighter-type airplane, it has only slight degree of static stability. While successive rolls usually compensated for one another,[12] there was a tendency for the major attitude changes in pitch to remain uncorrected as the airplane encountered successive gusts and drafts—a condition which resulted in climbing or diving. No attempt was made to control altitude displacements resulting from the drafts. Figures 12 and 13 show sample time variations in altitude and air speed that occurred on thunderstorm traverses using this technique.

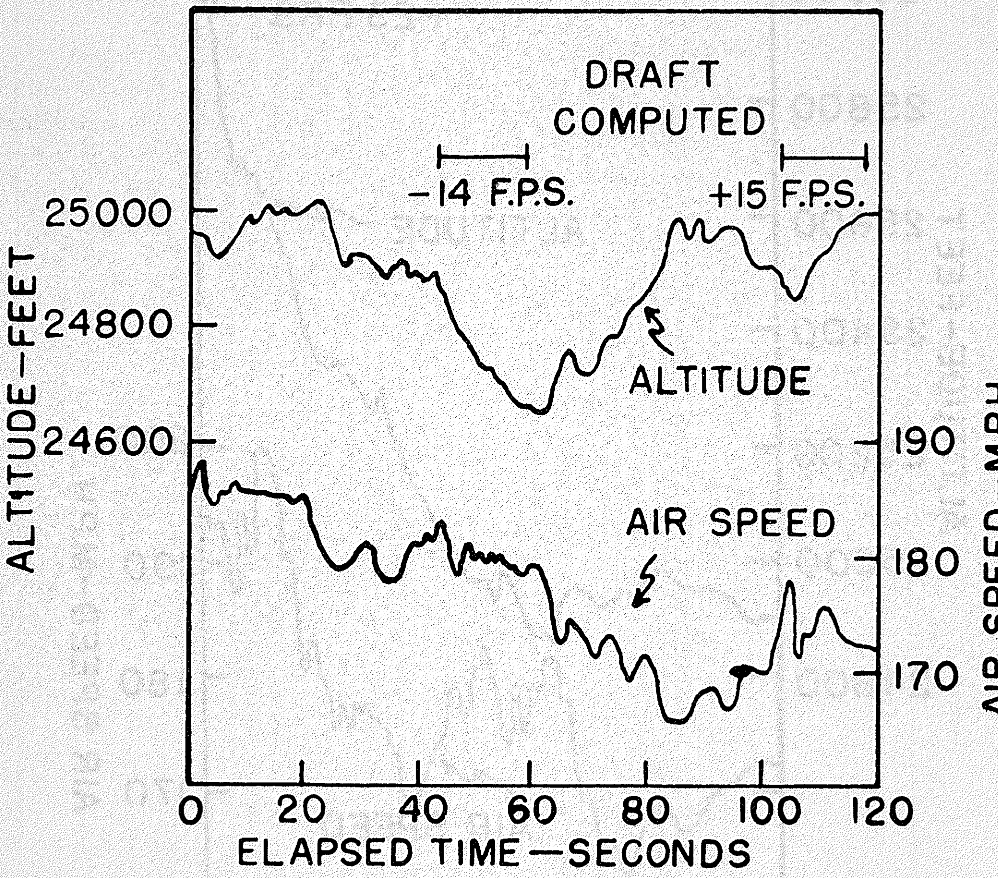

FIGURE 12.—Air speed and altitude changes that occurred on an average thunderstorm traverse.

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[11] Reduced speed was required in order to minimize the gust loads on the airplanes.

[12] Usually by the time a roll of 30° was reached, corrective action had been initiated.

In all flying done on the Project, navigational control was maintained by the master operational controller at the ground radar site. It was, therefore, unnecessary for the pilot to be primarily concerned with the airplane's location.

Except for a short period during the early part of the Florida season, all flights were made with wheels and flaps up.

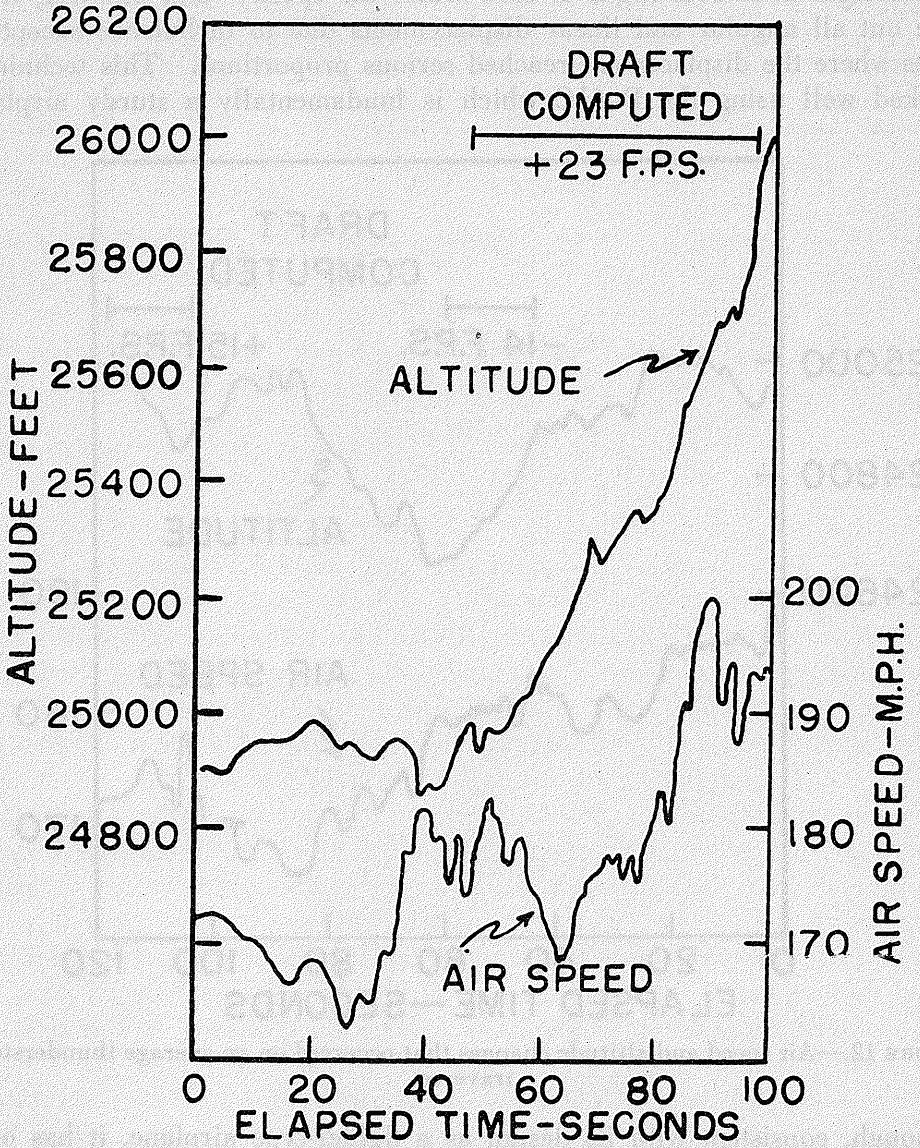

FIGURE 13.—Unusual air-speed and altitude changes that occurred on a thunderstorm traverse. Note that the air speed indicates a nose-down attitude in the updraft.

Conclusions

From the preceding discussion and the referenced publications of the Thunderstorm Project, one is led to the conclusion that the thunderstorm, as an environment in which it may be necessary to fly an airplane, is not the completely random, chaotic weather phenomenon that many had heretofore believed. Admittedly, it has a very complex structure; but it has been shown that the basic circulation features follow an identifiable pattern in the various stages of the storm's life cycle. Furthermore, it has been seen that there are definite altitude distributions of the weather elements within the storm (table 20).

TABLE 20.—*Summary of the intensities of the weather elements at the various altitudes of flight*

[Based on the tables included in earlier sections]

Weather phenomenon	Flight altitude (feet)				
	5,000	10,000	15,000	20,000	25,000
Gust velocities:					
U_e 4 fps	No significant variation within the lower 25,000 feet of the storm.				
U_e 14 fps	Minimum	----------	MAXIMUM	----------	Minimum
U_e 24 fps	Minimum	----------	----------	MAXIMUM	Minimum
Icing:					
All types	None	Infrequent	Frequent	MAXIMUM	Frequent
Clear and heavy rime	None	None	Infrequent	MAXIMUM	Frequent
Hail	None	MAXIMUM	MAXIMUM	Infrequent	Infrequent
Lightning strikes	Rare	Rare	Infrequent	Infrequent	Infrequent
Heavy rain	MAXIMUM	MAXIMUM	Frequent	Infrequent	None
Heavy snow	None	None	Infrequent	Frequent	Frequent

There is also reason to be optimistic about the possibility of being able to forecast such items as the maximum intensity of turbulence aloft and the intensity and direction of the gusty outflow winds at the surface.

There are many reasons why the development of these forecasting techniques will be slow, however. Among these is one brought out clearly by Thunderstorm Project operations; namely, that the present-day observation system does not report more than a very small sample of the thunderstorms that occur. This results from the fact that even in periods of strong air-mass convection the total area covered by thunderstorms is small. The obvious answer to this problem is the use of radar to provide a continual and complete synoptic coverage. Not only would such be of value to the meteorologist in determining the location and extent of thunderstorm activity but it would also be of inestimable value to traffic control in that it would be possible to see the locations of all airplanes at all times. In this regard, it is not unreasonable to make a simple transponding beacon part of the required equipment for an airplane to be cleared for instrument flying.

Perhaps certain items of the study of the thunderstorm as an environment should be pointed out: The levels near and slightly above the freezing level seem to contain the maximum occurrences of heavy icing, hail, and turbulence, and the majority of lightning strikes. From the draft displacement data, it is evident that the storm can be expected to displace the airplane from its entry altitude as much as 6,000 feet (at higher altitudes) in the maximum. Most drafts cause altitude changes considerably less than this amount. In the opinion of the pilots, who flew for the Project, this condition is not particularly serious except for (1) the slight possibility that the airplane be carried into the ground, or (2) the fact that in leaving assigned altitudes there is the chance of collision with other aircraft. However, the pilots feel that a positive source of danger exists in attempting to hold an assigned altitude with the result that the airplane is in nose-high or nose-low attitudes in the drafts. This unusual attitude coupled with the resulting airspeed changes can be the initiating circumstances for a spiral dive or an inadvertent stall. It must be remembered, however, that the practice of allowing the airplane to freely change altitude within a draft is in conflict with the regulations requiring adherence to an assigned flight level. Another problem—that of the airplane within the environment—is harder to evaluate. It has been demonstrated by NACA, however, that this problem is an important one which, under some circumstances, can exceed in importance the hazards of the storm itself. Unfortunately, data relative to this phase of thunderstorm study are meager and somewhat subjective.

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References

1. Byers, H. R., Holzman, B. G., and Maynard, R. H., 1946: A Project on Thunderstorm Microstructure, *Bull. Am. Meteor. Soc.*, Vol. 27, No. 4, 143–146.
2. White, F. D., 1946: The Thunderstorm Project: Operational Report on Phase I, *Bull. Am. Meteor. Soc.*, Vol. 27, No. 9, 549–550.
3. White, F. D., 1948: The Thunderstorm Project: Operational Report on Phase II. To be published in *Bull. Am. Meteor. Soc.*, Vol. 29.
4. 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.
5. 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.
6. Wexler, R., and Swingle, D. M., 1947: Radar Storm Detection, *Bull. Am. Meteor. Soc.*, Vol. 28, No. 4, 159–167.
7. M. I. T., Department of Meteorology, Weather Radar Research, 1946: *First Technical Report Under Signal Corps Contract.*

8. AAF Air Matériel Command, 1947: *Preliminary Report on New Techniques in Quantitative Radar Analysis of Rainstorms.*

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

10. Moses, H., 1948: *The Details of Surface Discontinuities Associated with Thunderstorms.* 16th Annual Meeting, Institute of Aeronautical Sciences, New York, N. Y.

11. Flight Research Loads Section, Langley Aeronautical Laboratory, NACA, 1941: *XC–35 Gust Research Project, Bulletin No. 1.*

12. Hydrometeorological Section, Office of Hydrologic Director, 1947: *Hydrometeorological Report No. 5, Thunderstorm Rainfall.*

13. George, J. J., 1947: Forecasting Turbulence in Thunderstorms, *Eastern Air Lines Meteorological Bulletin 47–38B*, and Supplements.

14. Helfand, B. B., 1947: Meteorological Conditions Associated with Flight Measurements of Atmospheric Turbulence, *NACA Technical Note No. 1273.*

15. U. S. Army Air Force, 1944: Instrument Flying Technique in Weather. *Tech. Order No. 30–100D–1.*

Appendix

(Extract from Supplement to Meteorological Bulletin 47–38B: "Forecasting Turbulence in Thunderstorms," issued by Eastern Air Lines, Inc.)

I. SITUATIONS IN WHICH THE RAOB GIVES EVIDENCE OF HAVING BEEN TAKEN IN OR NEAR THE ACTUAL THUNDERSTORM (in most cases, therefore, the noon sounding).

A. Determine from the raob the base of the convective type cloud (usually the point at which the R.H. increases to over 75 percent). This can usually be checked by comparing hourly reports from nearby surface stations.

B. Sketch in the moist adiabat which passes through this point which represents the cloud base. This moist adiabat must lie to the right of the curve (and therefore outline a "positive" area of energy).

C. Proceed up the sounding to the point where the R.H. decreases to less than 50 percent. The top of the convection-cloud will ordinarily be no more than 5,000 feet above this point except when fronts or line squalls occur.

D. Between these two points on the sounding, which delineate the vertical extent of the cloud-form, determine by comparison with the sketched-in moist adiabat the *greatest* temperature difference that occurs. *THIS IS THE TURBULENCE SCALE PARAMETER.*

The above steps apply only when the raob sounding, as it stands, indicates the presence of a thunderstorm, or a near thunderstorm, with the usual high moisture content and instability. It is these cases in which our forecasting tool works best, since these cases provided the data to establish the tool.

II. SITUATIONS IN WHICH THE RAOB SHOWS NO CONVECTIVE-TYPE CLOUDS PRESENT BUT THUNDERSTORMS DUE TO CONVECTION ARE FORECAST (in most cases, this involves forecasting the turbulence parameter from the midnight raob, when thunderstorms are forecast the next day).

A. To determine CCL: Average all mixing ratios reported below 900 mbs. Follow the corresponding constant mixing ratio line to the point of intersection with the sounding. This will be the base of the convective clouds when they develop. You can then sketch in the moist adiabatic lapse rate through this point upward and the dry adiabatic downward to surface pressure. This latter point will determine the temperature which must be reached before convective clouds will form. Check the CCL against the cloud heights reported the day before, making any necessary adjustments due to changes in air mass properties.

B. From here on, follow I, parts B, C, D. It will be noted that in effect the forecaster is forecasting the height of the cloud base in the thunderstorm, and basing his parameter for turbulence in such a forecast. This is less accurate than I, but will give very positive results in most cases. Advection of considerable moisture in lower levels will destroy much of the accuracy. Upstream raobs should be checked for such a possibility occurring.

III. SITUATIONS IN WHICH THE RAOB SHOWS NO CONVECTION-TYPE CLOUDS PRESENT BUT AN APPROACHING FRONTAL SURFACE IS FORECAST TO PRODUCE FRONTAL THUNDERSTORMS.

A. As in II. A., determine the mean moisture in lower level. It is essential here to carefully consider the probability of advection of very moist air in lower levels.

B. Using the initial point of the sounding, ascend dry adiabatically to point of intersection with the constant saturation mixing ratio line which is the average moisture from A.

C. This point is the lifting condensation level, and will be the approximate base of the cloud due to mechanical lifting of the air above the frontal surface.

D. From here on, follow I, parts B, C, and D.

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