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TECHNICAL NOTE

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ATMOSPHERIC TURBULENCE MEASUREMENTS

OBTAINED FROM AIRPLANE OPERATIONS AT ALTITUDES

BETWEEN 20,000 AND 75,000 FEET FOR SEVERAL

AREAS IN THE NORTHERN HEMISPHERE

By Thomas L. Coleman and Roy Steiner

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ATMOSPHERIC TURBULENCE MEASUREMENTS OBTAINED FROM AIRPLANE OPERATIONS AT ALTITUDES BETWEEN 20,000 AND 75,000 FEET FOR SEVERAL AREAS IN THE NORTHERN HEMISPHERE

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SUMMARY

Measurements of clear-air turbulence by use of airplane-borne instrumentation have been obtained from NASA VGH recorders during research flights of Lockheed U-2 airplanes to altitudes of 75,000 feet over several areas of the Northern Hemisphere. An analysis of these data has indicated that for the higher altitudes (50,000 to 75,000 feet), turbulence is both less frequent and less severe than for the lower altitudes (20,000 to 50,000 feet). Turbulence appears to be present at the high altitudes (60,000 to 75,000 feet) less than 1 percent of the time. Moderately heavy turbulence appears to exist on occasion at altitudes of about 50,000 feet over Japan. As a consequence, the gust experience appears to be more severe for operations over Japan than for the other areas. Less than 50 percent of the turbulent areas exceeded 10 miles in length.

INTRODUCTION

The National Aeronautics and Space Administration in cooperation with the Air Weather Service of the United States Air Force for a number of years operated a high-altitude flight research program to obtain detailed meteorological information for various geographic areas of the Northern Hemisphere. The participation of the NASA in the program consisted in obtaining information on the amount and intensity of atmospheric turbulence at high altitude for application to response studies of missiles and airplanes, whereas the aim of the Air Weather Service was to obtain data on humidity, pressure variations, and winds for operational and meteorological analyses. In order to obtain data at altitudes above the current operating level, the Lockheed U-2 airplane, which has altitude capabilities to 75,000 feet, was used in this investigation.

Some of the results on the frequency and intensity of the turbulence encountered at altitudes below 55,000 feet over the Western United States, Western Europe, Turkey, and Japan have been reported in references 1 to 3. These initial results have indicated somewhat lower gust frequencies and intensities for altitudes above 20,000 feet than the results given in reference 4 for the average turbulence conditions over the United States.

The overall sample of data on atmospheric turbulence for the four geographic areas (refs. 1 to 3) covered approximately 150,000 flight miles at altitudes between 20,000 and 55,000 feet. Data for the altitudes of 55,000 feet to 75,000 feet obtained at the same time as the data presented in references 1 to 3 and a sample obtained subsequently over the Southern United States have extended the sample size to 315,000 miles for altitudes above 20,000 feet. Approximately 90 percent of the flight miles were at altitudes above 40,000 feet. Although the samples of data are somewhat limited, especially for altitudes below 40,000, the results obtained appear to be of interest, particularly as regards to the turbulence at the higher altitudes. This paper summarizes the results presented in references 1 to 3 and extends the results to include the data to an altitude of 75,000 feet and to operations over the Southern United States. The results are presented in terms of the frequency of occurrence and intensity of the turbulence encountered at various altitudes for the five operations. These results are compared with earlier estimates of the average turbulence for operations over the United States for flight altitudes up to 60,000 feet.

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INSTRUMENTATION AND SCOPE OF DATA

The flight measurements were obtained during flights of several Lockheed U-2 airplanes. The Lockheed U-2 is a subsonic, straight-wing, single-engine, jet airplane originally designed for use as a high-altitude test vehicle. A photograph of a U-2 airplane is shown as figure 1.

The measurements pertinent to this investigation consisted of time-history records of airspeed, acceleration, and pressure altitude taken with NASA VGH recorders (ref. 5). The time histories were recorded on photographic paper moving at 4 inches per minute.

Inasmuch as the principal interest of the present program is in meteorological conditions at high altitudes, the flight plans for the operations were selected to provide maximum sampling time and coverage for altitudes above 50,000 feet. For this purpose, two types of flight plans were used, and these differed only in the altitudes selected for the cruise portion of the flight. The cruising altitudes were between about 45,000 and 55,000 feet for one flight plan and between 60,000 and 75,000 feet for the other. In each case, the flight operations consisted in climbing rapidly (rates of 2,000 to 5,000 ft/min) to the initial cruise altitude, cruising (with the altitude gradually increasing as the fuel load decreased), and then descending at approximately 2,000 feet per minute to the operations base.

The flights were made from bases at Watertown Strip, Nevada; Del Rio, Texas; Lakenheath, England; Wiesbaden, Germany; Adana, Turkey; and Atsugi, Japan. The average duration of flight was about $2\frac{1}{2}$ hours for the European operations, 6 hours for operations from Del Rio, Texas, and about 4 hours for the other operations. A variety of flight paths were flown from each of the bases in order to obtain a broad coverage of the geographic areas. The areas sampled in the five operations are indicated in figure 2. As shown in the figure, each sample was obtained within latitudes between approximately 30° north and 55° north.

The scope of the data samples in terms of the number of flights, total flight miles, and dates of record collection is summarized in table I. The table shows that the data from the Del Rio operations (Southern U.S), representing 35 flights which total 101,154 flight miles, constitute approximately 32 percent of the overall data sample. Each of the other data samples represent about 23 to 87 flights for totals of from about 32,000 to 83,000 flight miles. A breakdown of the data samples into the number of flight miles in various altitude intervals is given in table II. As shown in this table, the majority of the flight miles for each sample is contained within two altitude ranges: 45,000 to 55,000 feet and 60,000 to 75,000 feet. The concentration of the data collection in these two altitude ranges results, of course, from the manner in which the flights were planned, as was previously mentioned. The data samples at altitudes below about 40,000 feet, which were collected during the climb and descent phases of the flights, essentially represent soundings of the atmosphere in the general vicinity of the operating bases. The data at altitudes below 40,000 feet may be less representative of average turbulence conditions for the geographic areas than are the higher altitude data which were collected over much larger areas.

The flight schedules were based primarily on airplane and instrumentation availability and, in general, no attempt was made to schedule flights to sample turbulence for specific meteorological conditions. One exception to this procedure was in one of the flights in Japan, which was intentionally made over a typhoon in an attempt to obtain meteorological data at high altitude associated with this type of storm. This typhoon had largely dissipated when the flight was made, however, and no turbulence was encountered at the flight altitude of 65,000 feet.

Except for occasional penetrations of stable cloud formations in climbing or descending flight, the operations were in clear air.

EVALUATION OF DATA

The NASA VGH records were evaluated to obtain the derived gust velocities, the percent of rough air at various altitudes, and the length (along the flight path) of the turbulent areas encountered. The evaluation procedures are similar to the procedures used in references 1 to 3 and are reviewed briefly in the following paragraphs.

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The vertical gust velocities were derived through the use of the gust equation, which is given in reference 6 as

$$U_{de} = \frac{2a_n W}{m\rho_o K_g V_e S}$$

where

U_{de} derived gust velocity, fps

a_n peak normal acceleration, g units

W airplane weight, lb

S wing area, sq ft

K_g gust factor

V_e equivalent airspeed, fps

m wing lift-curve slope per radian

ρ_o air density at sea level, slugs/cu ft

In evaluating the records, values of the peak accelerations were read to a threshold sufficiently low to yield complete counts of all gust velocities greater than 2 feet per second. Simultaneous values of airspeed and pressure altitude were obtained from the records for each acceleration peak evaluated. The weight loss during flight was accounted for in determining the values of wing loading W/S for use in the equation. Appropriate values of the gust factor K_g (ref. 6), whose value is dependent on air density, airplane weight, and other airplane parameters, were computed for each part of the record where rough air was encountered. The values of the lift-curve slope m used in deriving the gust velocities were based on data obtained from the airplane manufacturer. The variation of the lift-curve slope m with Mach number is shown in figure 3.

It should be mentioned that the gust-velocity values presented herein may be affected to some extent by the effects of airplane flexibility and stability on the accelerations from which the gust velocities were computed. The magnitude of these effects is not known at present, and additional work is required before their influence on the gust-velocity values can be assessed.

For the purpose of determining the length of the turbulent areas and the percentage of time in rough air, the airplane was considered to be in rough air whenever the accelerometer trace was continuously disturbed and contained accelerations corresponding to gust velocities greater than 2 feet per second. This threshold value of 2 feet per second corresponds to that used in previous gust studies. The length of each turbulent area was found by multiplying the true airspeed by the time spent in the rough air. The summation of the lengths of the individual areas of rough air was divided by the total flight distance for given altitude intervals in order to obtain the percentage of rough air for that altitude interval.

RESULTS AND DISCUSSION

The gust velocities derived from the acceleration and airspeed data are presented as frequency distributions in table III for each operation and also for the combined or overall data sample. Table IV gives the frequency distributions of gust-velocity by 10,000-foot altitude intervals for the five individual data samples and also for the combined data. In addition, the number of miles in rough air and the total number of miles represented by each distribution are given in this table.

Frequency of Occurrence of Gust Velocities

Variation with geographic area.- In order to obtain an overall comparison of the frequency of occurrence of gust velocities for the different geographic areas, the average number of gusts per mile of flight which exceeded given values of gust velocity are given in figure 4(a) for the five individual operations. The curves in figure 4(a) represent operations at altitudes between 20,000 and 75,000 feet and were obtained by dividing the cumulative frequency distributions of gust velocity for each operation by the total flight miles flown (table III). Based on the total data samples for altitudes between 20,000 and 75,000 feet, figure 4(a) indicates that the gust frequency for the operations over Japan was significantly higher (on the order of 10 or 100 to 1) than for the other four operations.

In view of the relatively high gust frequency indicated in figure 4(a) for the operations over Japan, the data sample for this operation was examined in further detail. This examination showed that the high gust frequency for the Japanese operations resulted predominantly from two areas of rough air which were encountered at an altitude of approximately 52,000 feet on two separate flights over Honshu Island. The contribution of these two areas of rough air to the data is shown in table V by a comparison of the frequency distributions of gust velocities for the total Japanese data sample between 20,000 and 75,000 feet and for the two areas of rough air encountered at 52,000 feet. The table shows that over one-half of the gusts in the total Japanese data sample were experienced in the 151 miles of rough air encountered on one flight identified in the data schedules as flight CW-58-2 made over the eastern side of the mountains on the northern end of Honshu Island. The severity of this area of rough air is also evidenced by the relatively large gust velocities (maximum gust velocity = 20 fps) encountered during the flight. The 196-mile area of rough air encountered on another flight (flight CW-58-4 around the southern side of Shikohu Island located off the southern end of Honshu Island) also contributed a large number of gusts to the data sample but was of less severity than the rough air for flight CW-58-2.

In order to determine the effect of the two areas of rough air on the estimated gust frequencies, the gust velocities encountered in the two instances were omitted from the distribution of gust velocities for the Japanese operations, and the results obtained for the gust frequencies are shown in figure 4(b). Comparison of figures 4(a) and 4(b) shows that the omission of these two areas of rough air drastically reduces the gust frequency indicated for Japan and tends to make the turbulence experience for this operation approximately equal to that measured over the United States and Western Europe.

In order to determine whether the two cases of moderately heavy turbulence encountered over Japan were truly representative occurrences or were merely reflections of very unusual combinations of conditions, the meteorological conditions existing at the times of the two flights were examined. Consideration of the surface and upper air charts for these two days (Jan. 22, 1958 for flight CW-58-2 and Feb. 26, 1958 for flight CW-58-4) showed that in both cases the Japanese Islands were under the influence of moderately severe surface storms and that well developed jet streams with peak wind velocities of about 200 knots existed at altitudes of about 35,000 feet over the Islands. At the flight altitude of 52,000 feet, the winds were between 100 and 150 knots. These weather conditions would be expected to be conducive to turbulence development. An additional factor which may be significant is that the mountainous terrain of Japan in combination with the strong jet streams may be expected to give rise to mountain wave phenomena (ref. 7) which, in turn, is conducive to formation of turbulence at high altitude. Strong jet streams are quite common over Japan, especially during the winter months, and the present test conditions by no means represent the strongest jet-stream developments that may be expected. Consequently, it appears that the turbulence levels measured on flights CW-58-2 and CW-58-4 represent fairly normal rather than unusual or extreme conditions. Additional tests are required, however, in order to obtain a good estimate of the frequency with which such turbulence occurs.

Variation with altitude.- Previous investigations (ref. 4, for example) have indicated that for altitudes up to about 60,000 feet, the frequency of occurrence of gust velocities decreased with increasing altitude. In order to determine whether this trend continued to higher altitude, the average number of gusts which exceeded given values of gust velocity per mile of flight within given altitude intervals is shown in figure 5 for each of the five operations. The gust frequency for each operation is seen to be significantly lower for the highest altitude interval (60,000 to 75,000 feet) than for the lowest altitude interval. In terms of the gust intensity, the results indicate that the maximum gust velocity experienced per mile of flight between 60,000 and 75,000 feet is on the order of 1/4 or 1/2 that experienced per mile of flight between 20,000 and 40,000 feet. In addition, it may be noted that for each operation except the one over Japan, the gust frequency shows an orderly decrease with increasing altitude. The reason for the deviation of the Japanese results from the general pattern of decreasing gust frequency with increasing altitude has been discussed previously.

It is of interest to compare the present results on the gust frequencies with previous estimates. For this purpose, estimates of the gust frequency at the various altitudes based on the results in reference 4 for average operations over the United States are also shown in figure 5. The results from reference 4 are based on the basic distribution of nonstorm turbulence and the estimated variation of the gust intensity with altitude. These reference results did not extend to altitudes above 60,000 feet and, consequently, no estimate is given for the highest altitude interval of figure 5.

Comparison of the two sets of results in figure 5 shows that the gust frequencies measured over each of the geographic areas were substantially lower in all except one instance than the corresponding results obtained from reference 4. The gust frequencies measured between 40,000 and 60,000 feet over Japan are significantly higher than the corresponding results from reference 4 and are, in fact, approximately equal to results for the lower altitude interval (20,000 to 40,000 feet) of reference 4. The gust frequencies measured over the United States are in better agreement with the estimates of reference 4 than are the results from the other three operations. This result is not surprising inasmuch as the estimates of reference 4 were originally derived for average operations over the United States. From the overall viewpoint, the comparison in figure 5 indicates that estimates of clear air gust frequencies based on reference 4 may be too high for altitudes above 20,000 feet.

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Percentage of Flight Distance in Rough Air

The percentage of the flight distance which was in rough air is presented for each operation in figure 6 by 5,000-foot altitude intervals in the altitude range between 20,000 and 75,000 feet. The results show that for altitudes between 40,000 and 75,000 feet, rough air was generally encountered less than 3 percent of the time. Each set of data shows a maximum peak at altitudes between 30,000 and 40,000 feet in the variation of the percentage of rough air with altitude. In this altitude interval, the percentage of rough air over the United States and Japan appears to be significantly higher than over Western Europe and Turkey. The increase in the amount of rough air at altitudes between 30,000 and 40,000 feet is probably due to the high winds and wind shears associated with jet streams which are normally prevalent at these altitudes for the midlatitude areas covered by the data (refs. 8 and 9).

A comparison of the variation in the percent of rough air with altitude based on the combined data sample with corresponding results from reference 4 is shown in figure 7. In comparison with the reference results, the present data indicate that rough air exists a larger percentage of the time at altitudes between 30,000 and 40,000 feet. The rough air is, however, of low intensity. For operations at altitudes between 60,000 and 75,000 feet, the results indicate that rough air would, on the average, be encountered less than 1 percent of the time.

Lengths of Turbulent Areas

The probability distributions of the lengths of the turbulent areas encountered in each operation are given in figure 8. The five curves in the figure show the probability that an area of turbulence will exceed a given length. Inspection of the results shows that the probability of exceeding a given length of turbulent area decreases rapidly with increasing length. The results indicate, for example, that less than

50 percent of the turbulent area exceeded 10 miles in length. For three operations, only about 1 percent of the turbulent areas exceeded 30 miles in length. In contrast, for the operations over Japan and the Southern United States, approximately 10 percent of the turbulent areas exceeded 30 miles in length. The turbulence associated with the turbulent areas of 150 to 200 miles in length encountered over Japan was fairly severe for an altitude of 50,000 feet and was apparently caused by strong jet streams, surface storms, and mountain wave phenomena. In constrast, several turbulent areas of 50 to 80 miles in length were encountered over the Southern United States but were of relatively low intensity. The two largest turbulent areas (approximately 80 miles in length) were encountered during descent from approximately 50,000 feet. One case on May 20, 1959, indicated a turbulent area approximately 30,000 feet in thickness extending from an altitude of 45,000 feet to 15,000 feet. This flight occurred during the season of rather severe convective activity over the flight area, and thunderstorms were observed in the general area of the base of operations.

CONCLUSIONS

Initial measurements of atmospheric turbulence by use of airplane-borne instrumentation have been obtained from NASA VGH recorders during research flights of Lockheed U-2 airplanes to altitudes of 75,000 feet. Measurements covering a total of over 315,000 flight miles have been obtained from operations over five geographic areas: Western United States, Southern United States, Western Europe, Turkey, and Japan. An analysis of these data has indicated that:

1. For the higher flight altitudes (60,000 to 75,000 feet), turbulence is both less frequent and less severe than for the lower altitudes (20,000 to 60,000 feet). Turbulence appears to be present at the high altitudes less than 1 percent of the time. The frequency of occurrence of given values of gust velocity for the high altitudes is roughly 1/10 of that for the lower altitudes.

2. In general, the intensity of the turbulence decreases in an orderly pattern with increasing altitude throughout the altitude range (20,000 to 75,000 feet) covered by the data. A notable exception to this orderly pattern is present in the data for the operations over Japan, however, in that the altitude interval of 40,000 to 60,000 feet appears more turbulent than the lower altitude interval (20,000 to 40,000 feet). Moderately heavy turbulence appears to exist on occasion at altitudes of about 50,000 feet over Japan and is apparently associated with the strong character of the jet stream in this area and probably also with a mountain-wave phenomenon. As a consequence of this type of

condition, the gust experience appears to be more severe for operations over Japan than over the other four geographic areas. Additional data are needed, however, in order to establish the frequency of occurrence of the moderately severe turbulence condition over Japan.

3. In general, the present results indicate that turbulence at altitudes from 20,000 to 75,000 feet is less severe than is indicated by previous estimates given in NACA TN 4332.

4. The results indicate that for altitudes of 20,000 to 75,000 feet,
less than 50 percent of the turbulent areas exceeded 10 miles in length. L
For operations over three of the geographic areas, only about 1 percent 1
of the turbulent area exceeded 30 miles in length. For the operations 2
over Japan and the Southern United States, however, approximately 5
10 percent of the turbulent areas exceeded 30 miles in length. 4

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., August 4, 1960.

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TABLE I.- SCOPE OF DATA SAMPLES

Sample	Number of flights	Total flight miles	Dates of record collection
Southern United States	35	101,154	November 1958 to December 1959
Western United States	24	53,944	May 1956 to March 1957
Western Europe	87	83,552	May 1956 to October 1957
Turkey	23	32,105	November 1956 to June 1957
Japan	23	44,263	May 1957 to February 1958

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TABLE II.- DISTRIBUTION OF TOTAL FLIGHT MILES BY

ALTITUDES FOR FIVE DATA SAMPLES

Altitude, ft	Total flight miles					
	Southern United States	Western United States	Western Europe	Turkey	Japan	Combined
20,000 to 25,000	703	695	3,153	333	890	5,774
25,000 to 30,000	746	508	3,754	451	602	6,061
30,000 to 35,000	819	609	3,263	693	698	6,082
35,000 to 40,000	1,528	821	5,632	978	1,172	10,131
40,000 to 45,000	1,159	1,358	6,316	1,152	1,421	11,406
45,000 to 50,000	1,397	5,604	10,528	4,497	4,642	26,668
50,000 to 55,000	1,772	30,244	27,868	7,561	23,192	90,637
55,000 to 60,000	8,394	1,658	3,351	1,012	436	14,851
60,000 to 65,000	73,596	2,597	6,811	2,966	826	86,796
65,000 to 70,000	11,040	5,787	12,708	12,462	7,581	49,578
70,000 to 75,000	0	4,063	168	0	2,803	7,034
Total	101,154	53,944	83,552	32,105	44,263	315,018

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TABLE III.- FREQUENCY DISTRIBUTIONS OF DERIVED GUST VELOCITY FOR THE COMBINED DATA SAMPLE AND FIVE INDIVIDUAL DATA SAMPLES

[Altitude, 20,000 to 75,000 ft]

Gust velocity, U_{de}, fps	Frequency for:					
	Southern United States	Western United States	Western Europe	Turkey	Japan	Five samples combined
2 to 3	280	389	660	148	981	2,458
3 to 4	120	113	271	67	465	1,036
4 to 5	32	48	83	15	257	435
5 to 6	15	19	29	3	134	200
6 to 7	7	16	19		102	144
7 to 8	6	4	6		58	74
8 to 9	0	2	3		28	33
9 to 10	1	1			23	25
10 to 11		1			13	14
11 to 12		1			6	7
12 to 13		1			4	5
13 to 14					1	1
14 to 15					1	1
15 to 16					0	0
16 to 17					3	3
17 to 18					0	0
. . .						
20 to 21					1	1
Total	461	595	1,071	233	2,077	4,437
Total flight miles	101,154	53,944	83,552	32,105	44,263	315,018

TABLE IV.- FREQUENCY DISTRIBUTION OF DERIVED GUST VELOCITY

FOR VARIOUS ALTITUDE INTERVALS FOR FIVE SAMPLES

[Coding in column headings is: SUS, Southern U.S.; WUS, Western U.S.; WE, Western Europe; T, Turkey; J, Japan]

Gust velocity, U_{de}, fps	Frequency at altitude of:																	
	20,000 to 30,000 ft						30,000 to 40,000 ft						40,000 to 50,000 ft					
	SUS	WUS	WE	T	J	Total	SUS	WUS	WE	T	J	Total	SUS	WUS	WE	T	J	Total
2 to 3	28	142	230	15	54	469	172	83	212	28	103	598	45	18	92	85	31	271
3 to 4	13	41	85	2	20	161	61	13	91	8	29	202	37	1	58	38	13	147
4 to 5	4	16	33		6	59	22	4	23	2	15	66	4		12	12	5	33
5 to 6	2	8	12		3	25	7	1	9	1	2	20	4		5	2		11
6 to 7	5	6	5		1	17	2	1	5		2	10	0		5			5
7 to 8	2	1	2		1	6	3		2			5	1		2			3
8 to 9		1	2			3	0					0						
9 to 10		0				0	1					1						
10 to 11		1				1												
11 to 12		0				0												
12 to 13		1				1												
13 to 14																		
14 to 15																		
Total	54	217	369	17	85	742	268	102	342	39	151	902	91	19	174	137	49	470
Rough-air miles	158	114	317	5	151	745	278	216	472	52	262	1,280	113	57	239	138	74	621
Total flight miles	1,449	1,203	6,907	784	1,492	11,835	2.347	1,430	8,895	1,671	1,870	16,213	2,556	6,962	16,844	5,649	6,063	38,074

TABLE IV.- FREQUENCY DISTRIBUTION OF DERIVED GUST VELOCITY FOR

VARIOUS ALTITUDE INTERVALS FOR FIVE SAMPLES - Concluded

Gust velocity, U_{de}, fps	Frequency at altitude of:																	
	50,000 to 60,000 ft						60,000 to 70,000 ft						70,000 to 75,000 ft					
	SUS	WUS	WE	T	J	Total	SUS	WUS	WE	T	J	Total	SUS	WUS	WE	T	J	Total
2 to 3	17	122	93	15	676	923	18	20	33	5	117	193		4				4
3 to 4	7	57	31	17	382	494	2	1	6	2	21	32						
4 to 5	2	28	12		220	262			3	1	11	15						
5 to 6	2	10	3		128	143					1	1						
6 to 7		9	4		99	112												
7 to 8		3	0		57	60												
8 to 9		1	1		28	30												
9 to 10		1			23	24												
10 to 11		0			13	13												
11 to 12		1			6	7												
12 to 13					4	4												
13 to 14					1	1												
14 to 15					1	1												
15 to 16					0	0												
16 to 17					3	3												
17 to 18					0	0												
18 to 19					0	0												
19 to 20					0	0												
20 to 21					1	1												
Total	28	232	144	32	1,642	2,078	20	21	42	8	150	241		4				4
Rough-air miles	251	367	263	55	1,058	1,994	232	30	57	3	156	478	0	9	0	0	0	9
Total flight miles	10,166	31,902	31,219	8,573	23,628	105,488	84,636	8,384	19,519	15,428	8,407	136,374	0	4,063	168	0	2,803	7,034

TABLE V.- FREQUENCY DISTRIBUTIONS OF DERIVED GUST VELOCITY FOR TOTAL SAMPLE OF DATA FROM JAPANESE OPERATIONS AND FOR SAMPLES FROM TWO AREAS OF ROUGH AIR ENCOUNTERED ON FLIGHTS CW-58-2 AND CW-58-4 OVER JAPAN

Gust velocity, U_{de}, fps	Frequency for:		
	Total sample	Flight CW-58-2	Flight CW-58-4
2 to 3	981	396	120
3 to 4	465	255	65
4 to 5	257	173	31
5 to 6	134	119	9
6 to 7	102	87	7
7 to 8	58	55	2
8 to 9	28	26	2
9 to 10	23	22	0
10 to 11	13	13	0
11 to 12	6	6	0
12 to 13	4	4	0
13 to 14	1	1	0
14 to 15	1	0	1
15 to 16	0	0	
16 to 17	3	3	
17 to 18	0	0	
18 to 19	0	0	
19 to 20	0	0	
20 to 21	1	1	
Total $U_{de} \geqq 2$ fps	2,077	1,161	237
Miles of rough air	1,701	151	196

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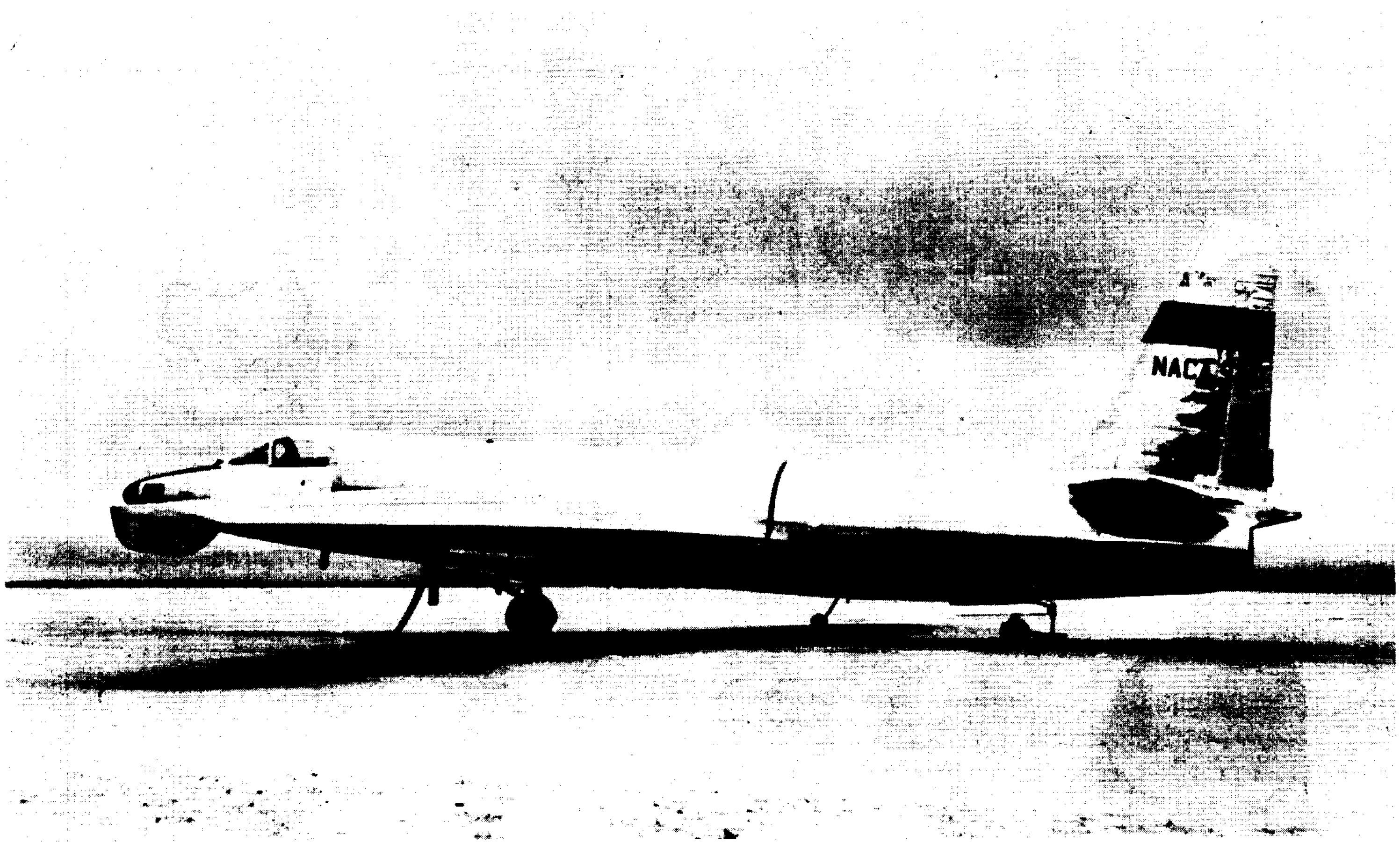


L-57-96

Figure 1.- Lockheed U-2 airplane used by NASA for gust-meteorological studies at high altitude.

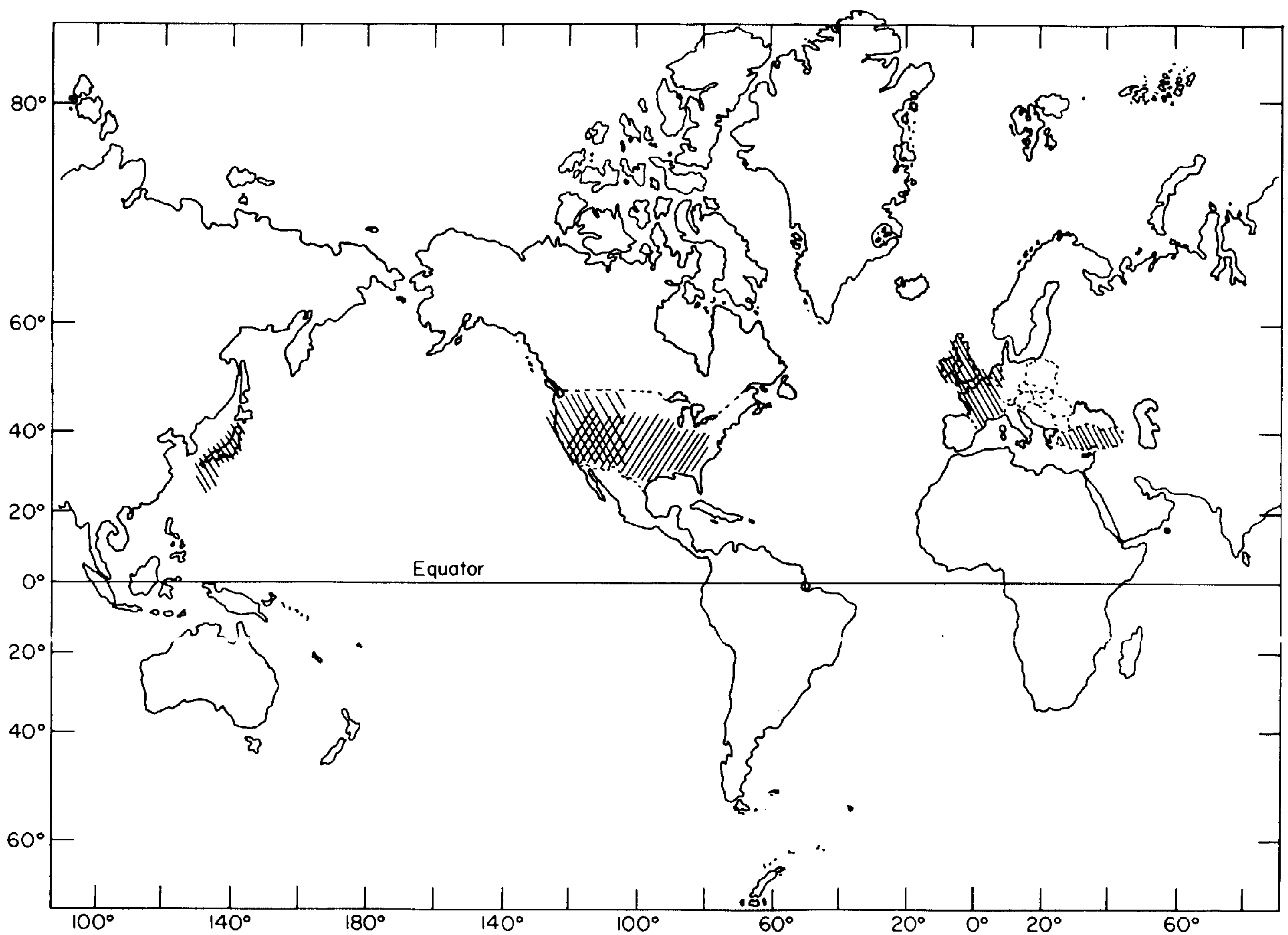


Figure 2.- Geographic areas sampled during five operations.

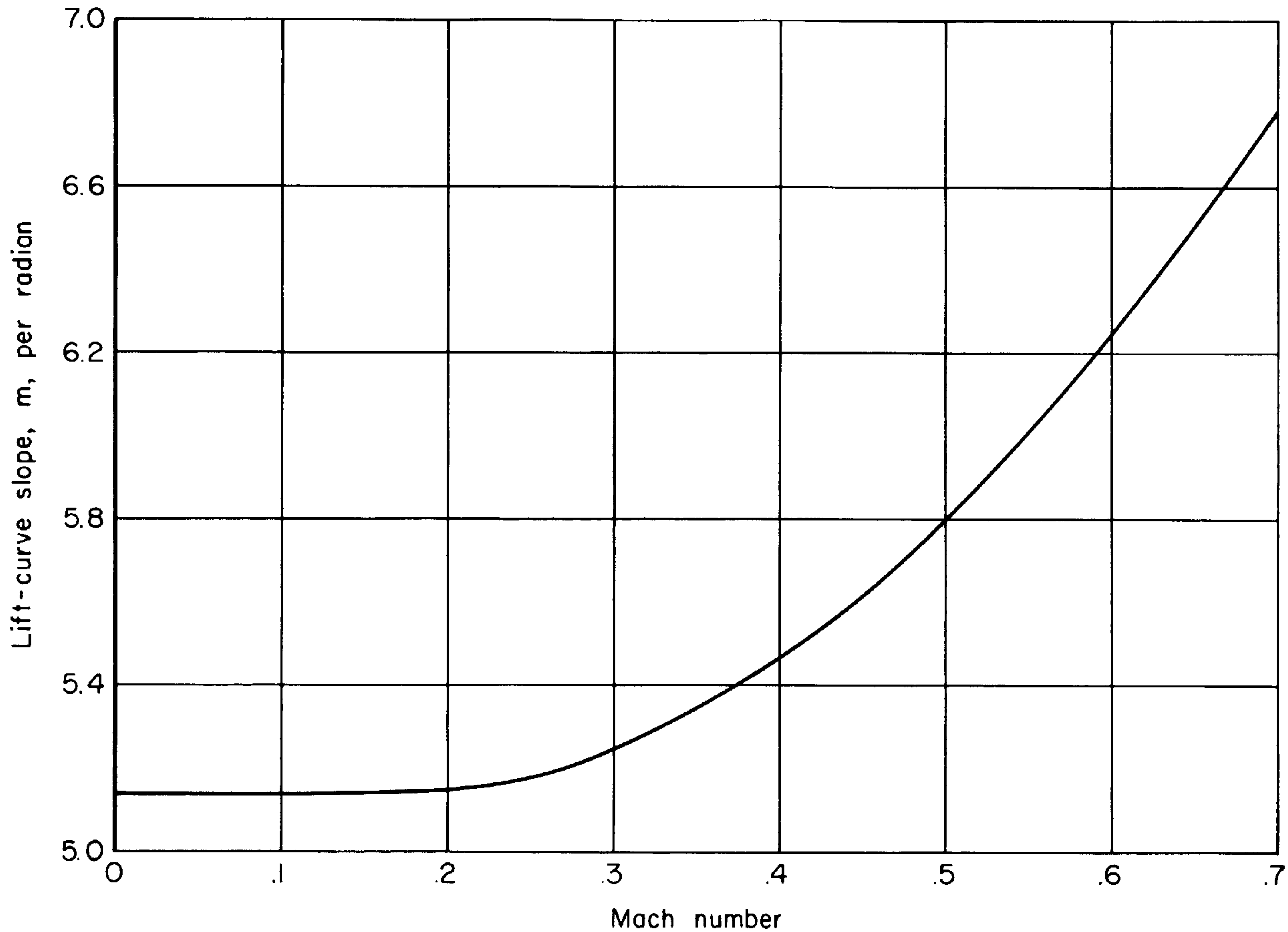
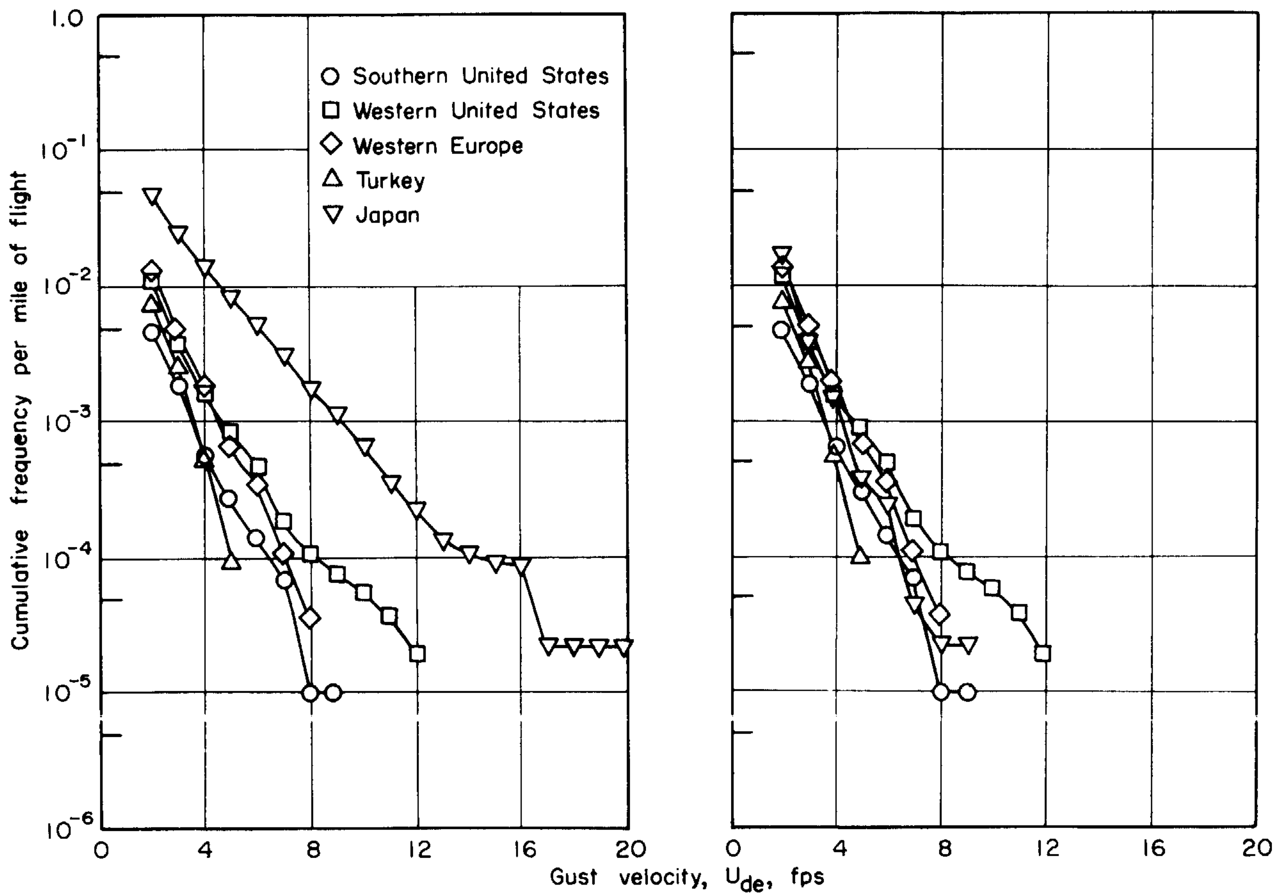


Figure 3.- Variation of lift-curve slope with Mach number.



(a) All data.

(b) Data for which two areas of turbulence on flights CW-58-2 and CW-58-4 are omitted.

Figure 4.- Comparison of the frequency of exceeding given values of gust velocity per mile of flight for five operations.

L-1254

L-1254

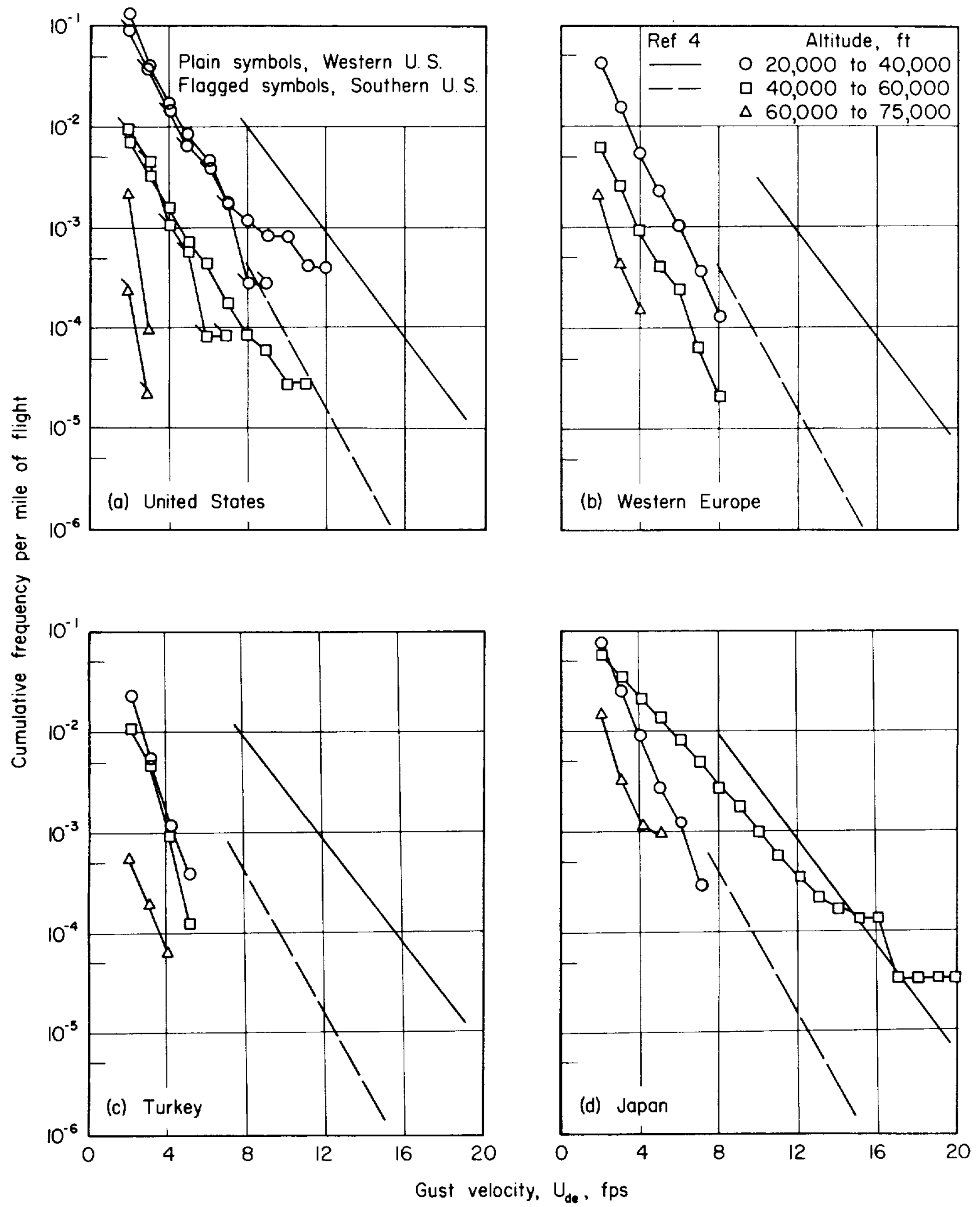


Figure 5.- Variation of the frequency of exceeding given values of gust velocity per mile of flight with altitude for four geographic locations.

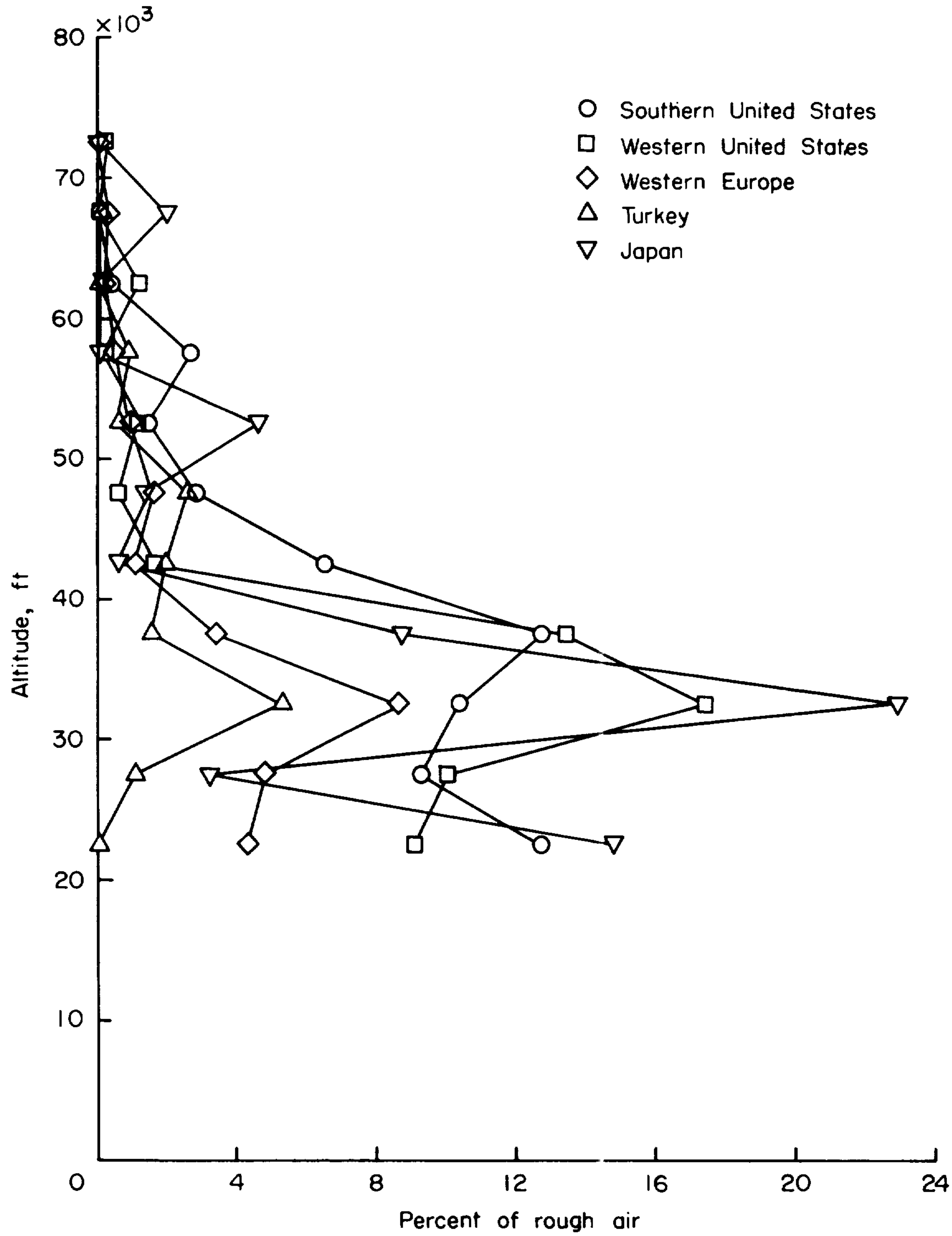


Figure 6.- Variation in percentage of rough air with altitude for five samples.

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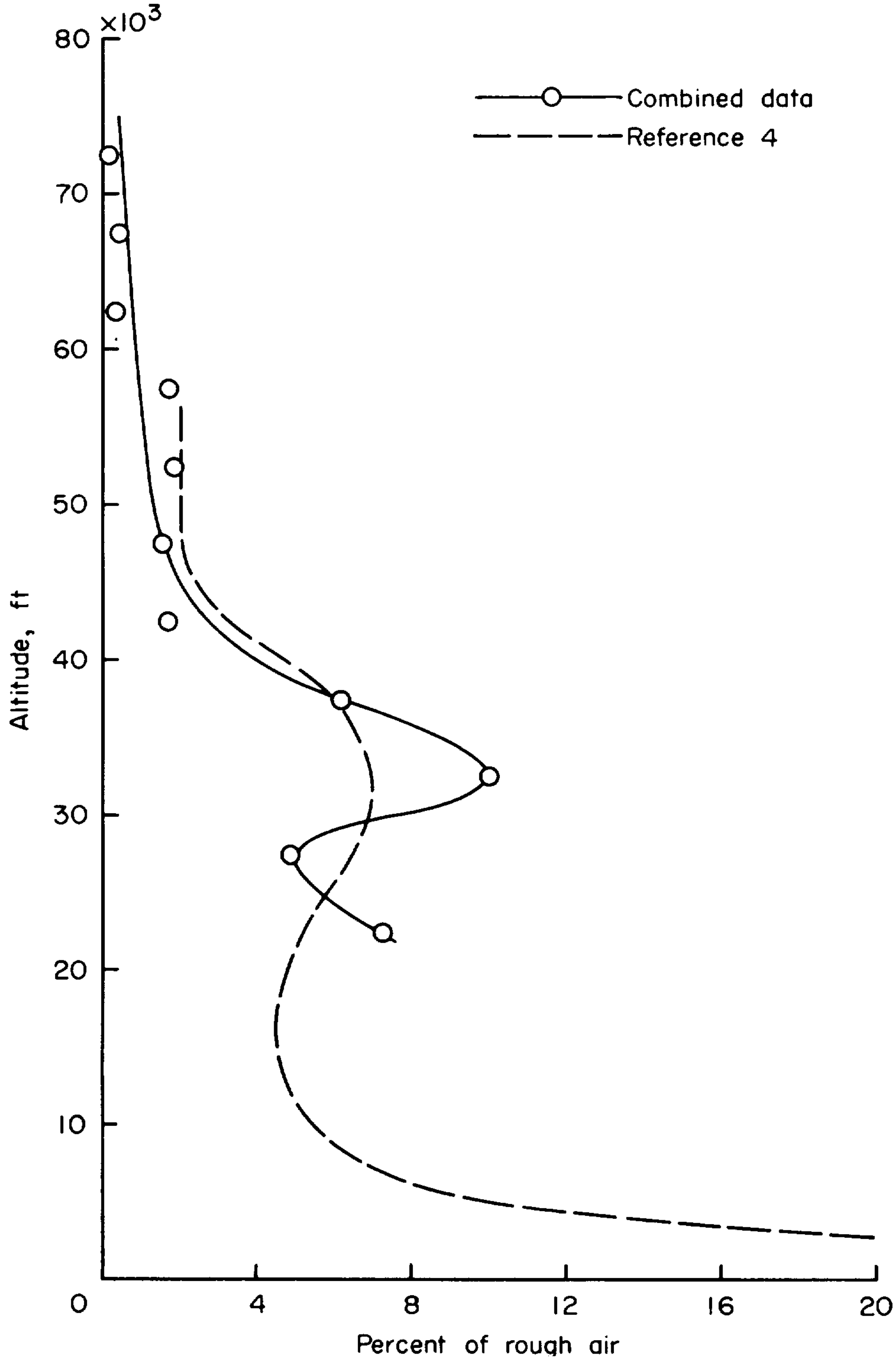

Figure 7.- Variation in percentage of rough air with altitude.

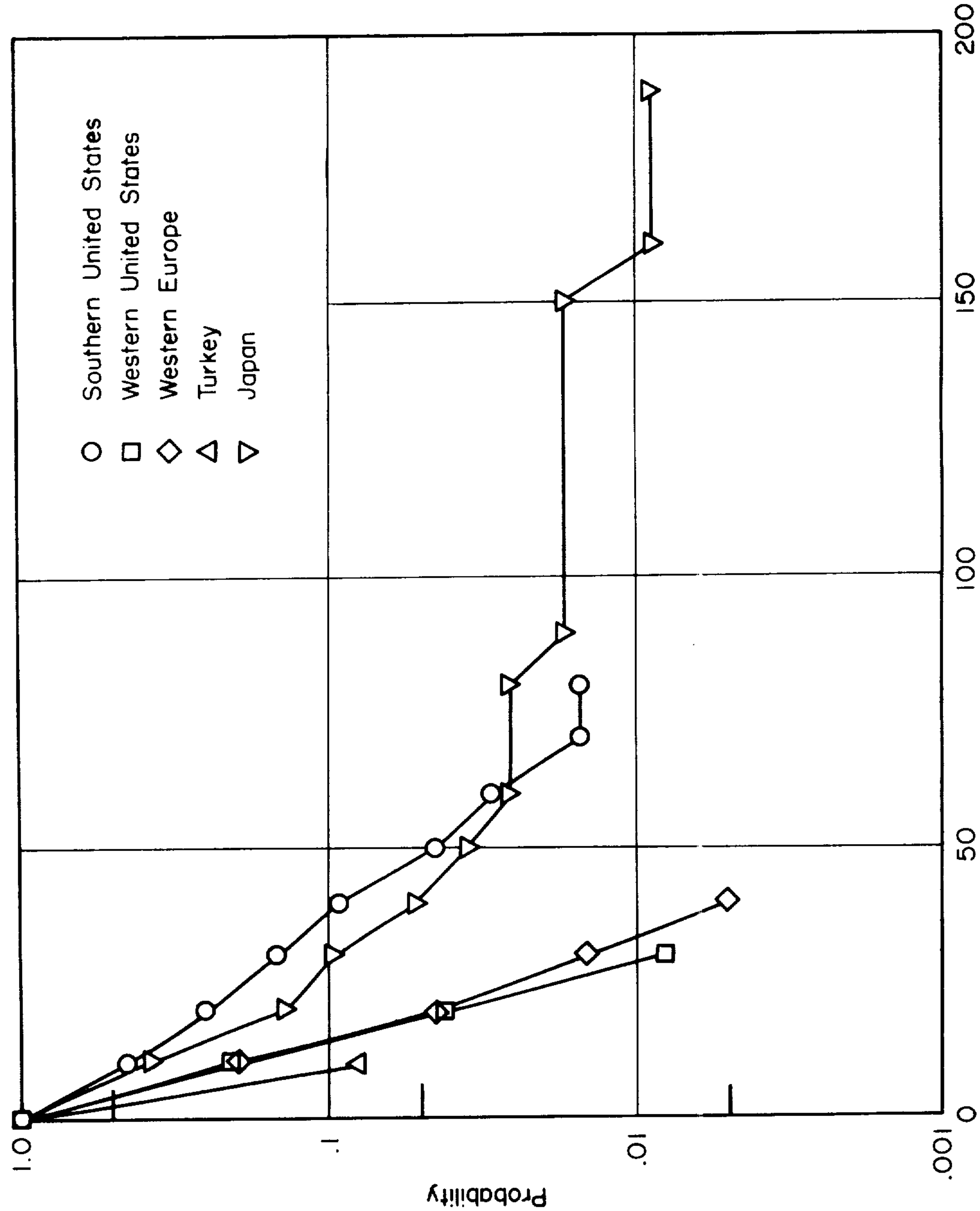

Figure 8.- Probability that turbulent area will exceed a given length.