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AIRPLANE MEASUREMENTS OF ATMOSPHERIC TURBULENCE AT ALTITUDES BETWEEN 20,000 AND 55,000 FEET FOR FOUR GEOGRAPHIC AREAS

By Thomas L. Coleman and May T. Meadows

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Langley Field, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON
June 1959

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SUMMARY

Measurements of clear-air turbulence by use of airplane-borne instruments have been obtained from NACA VGH recorders during research flights of Lockheed U-2 airplanes at altitudes between 20,000 and 55,000 feet over Western United States, England and Western Europe, Turkey, and Japan. An analysis of these data has indicated that at the higher altitudes (40,000 to 55,000 feet) turbulence is both less frequent and less severe than at the lower altitudes (20,000 to 40,000 feet). Turbulence appears to be encountered at the high altitudes for only about 2 percent of the flight distance as compared with 5 percent or more at the lower altitudes. Moderately heavy turbulence exists on occasion at altitudes of about 50,000 feet over Japan and appears to be associated with the strong character of the jet stream in this area and also with a mountain-wave phenomenon.

INTRODUCTION

Recently, the National Aeronautics and Space Administration, in cooperation with the Air Weather Service of the United States Air Force, initiated a high-altitude flight-research program aimed at providing detailed meteorological information for various geographic areas of the world. The primary purpose of the NASA participation in the program was to obtain information on the amount and intensity of atmospheric turbulence at high altitudes for application to response studies of missiles and airplanes; whereas, the aim of the Air Weather Service was to collect data on humidity, pressure variations, and winds for operational and meteorological analyses. In order to obtain data at altitudes above the current normal operating level, the Lockheed U-2 airplane is being used in the investigation. Inasmuch as the U-2 airplane is capable of extended flight at altitudes between 50,000 and 55,000 feet, a significant increase in the altitudes that may be sampled with airplane-borne instruments is possible.

In order to obtain data samples from various geographic areas, flight operations have been conducted from four widely separated locations. The initial operations were undertaken over the western part of the United States and over Western Europe in the spring of 1956. The results from these operations (refs. 1 and 2) indicated somewhat lower gust frequencies and gust intensities than did the previous estimates given in reference 3 for average turbulence conditions over the United States and, in part, formed the basis for the turbulence estimates given in reference 4.

Since publication of references 1 and 2, data samples have been obtained from operations over Turkey and Japan, and additional data have been obtained from the operations over Western Europe. The combined sample of data on atmospheric turbulence for the four operations presently covers approximately 150,000 flight miles at altitudes between 20,000 and 55,000 feet. This report summarizes the results obtained for the frequency and intensity of the turbulence encountered at various altitudes in the four operations. In addition, the results on the variation of the percent of flight distance in rough air with altitude are compared with the estimates given in references 3 and 4.

INSTRUMENTATION AND SCOPE OF DATA

Atmospheric-turbulence data 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 the test airplane is shown in figure 1.

The measurements pertinent to this report consisted of time histories of airspeed, acceleration, and pressure altitude taken with NACA VGH recorders (ref. 5). The time histories were recorded on photographic paper moving at four inches per minute.

Inasmuch as the major 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 at altitudes between 45,000 and 55,000 feet. In general, the flight plans consisted of climbing to an altitude of approximately 45,000 feet in the vicinity of the operations base, cruising with the altitude gradually increasing as the fuel load decreased, and then descending to the operations base. As a consequence of this flight procedure, the gust measurements below approximately 45,000 feet were obtained primarily during the climb and descent phases of the flights and essentially represent soundings of the atmosphere in the general vicinity of the operations bases.

The flights were made from bases at Watertown Strip, Nevada; Lakenheath, England; Wiesbaden, Germany; Adana, Turkey; and Atsugi, Japan. (Two additional flights were made from a base in Alaska, and these data have been combined with those from Japan.) 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 four operations are indicated in figure 2. As shown in the figure, the samples were collected mainly between latitudes 30° N and 55° N.

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 Western Europe, which represent 87 flights and total 60,514 flight miles, constitute approximately 40 percent of the combined data sample. Each of the other data samples represents about 23 flights and consists of about 15,000 flight miles for the operations over Turkey to 40,000 flight miles over the western part of the United States. A breakdown of the data samples into the number of miles flown within the various altitude intervals is given in table II. As shown in the table, the majority of the flight miles for each sample was obtained at altitudes between 45,000 and 55,000 feet.

The flight schedules were based primarily on airplane and instrumentation availability and, in general, attempts were not made to schedule flights to sample turbulence for specific meteorological conditions. (One exception to this procedure was that one of the flights from Japan was specifically made over a reported 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.) Except for occasional penetrations of stable cloud formations while climbing or descending, the present operations were in clear air.

EVALUATION OF DATA

The NACA 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.

The derived gust velocities were calculated from simultaneous readings of peak acceleration, airspeed, and altitude 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, the accelerations were read to a threshold sufficiently low to yield frequency counts of all gust velocities greater than 2 feet per second. The values of wing loading W/S used in the equation took into consideration the in-flight weight loss due to fuel consumption. Appropriate values of the gust factor K_g 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. (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, however, and additional work is required before their influence on the gust-velocity values can be assessed.)

For the purpose of determining the horizontal extent, or length, of the turbulent areas, 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 is approximately the same as that used in previous gust studies, such as references 2 and 3. The length of each turbulent area was found simply by multiplying the true airspeed by the time spent in rough air. The summation of the lengths of the individual areas of rough air was then divided by the total flight distance for given altitude intervals in order to obtain the percent of flight distance in 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 data sample. Table IV gives the frequency distributions of gust velocity by 10,000-foot altitude intervals for the four geographic areas of operation and also for the combined data. In addition, the number of miles of flight in rough air and the total number of miles represented by each distribution are given in tables III and IV.

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 3(a) for the four geographic areas of operation. The curves in figure 3(a) represent operations between 20,000 and 55,000 feet and were obtained by dividing the cumulative frequency distributions of gust velocity for each area of operation by the total miles of flight given in table III. Based on the total data samples between 20,000 and 55,000 feet, figure 3(a) indicates that the gust frequency for the operations over Japan was significantly higher than that for the other three operations. The gust frequencies for the operations over the western part of the United States and Western Europe were approximately equal and tended to be somewhat higher than the gust frequency for the operations over Turkey.

In view of the relatively high gust frequency indicated in figure 3(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 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 in which are presented the frequency distributions of gust velocities for the total Japanese data sample between 20,000 and 55,000 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 January 22, 1958 (flight CW-58-2).

The 196 miles of rough air encountered on February 26, 1958 (flight CW-58-4) also contributed a large number of gusts to the data sample but the rough air in this flight was of less severity than that in flight CW-58-2.

In order to determine the effect of these two areas of rough air on the estimated gust frequency, the gust velocities encountered in the two flights were omitted from the distribution of gust velocities for the Japanese operations and the results are shown in figure 3(b). Comparison of figures 3(a) and 3(b) shows that the omission of these two areas of rough air tends to make the turbulence experience for this operation more comparable with that measured over the United States, Western Europe, and Turkey.

In order to ascertain whether the two cases of moderately heavy turbulence encountered over Japan were representative occurrences or merely reflected very unusual conditions, the meteorological conditions existing at the times of the two flights were examined. Consideration of the surface and upper-air charts for the two days of the flights showed that on both days the Japanese islands were under the influence of moderately severe surface cyclonic storms and that well-developed jet streams with peak wind velocities of about 200 knots existed at about 35,000 feet over the islands. These weather conditions would be expected to be conducive to the development of turbulence. In addition, the strong jet streams in combination with the mountainous terrain of Japan may be expected to give rise to mountain-wave phenomena (ref. 7) which, in turn, are conducive to the formation of turbulence at high altitude. Severe cyclonic storms and strong jet streams are quite common over Japan, especially during the winter months, and the weather conditions for the two days on which moderately heavy turbulence was encountered do not appear to represent unusual conditions. In view of these considerations, it would appear that the turbulence levels measured on flights CW-58-2 and CW-58-4 may represent a frequent occurrence rather than extreme conditions. Additional data are required, however, in order to obtain a reliable estimate of the frequency with which such turbulence conditions occur.

Variation with altitude.- Previous investigations (ref. 3, for example) have indicated that the frequency of occurrence of gust velocities generally decreased with increasing altitude. In order to examine the variation of the gust frequency with altitude for the present operations, the gust-velocity data for the combined data sample given in table IV are plotted in figure 4(a) in terms of the average number of gusts which exceeded given values of gust velocity per mile of flight within given altitude intervals. The results in figure 4(a) indicate that the gust frequency decreased with increasing altitude between 20,000 and 50,000 feet. The gust frequency for the altitude interval from 50,000 to 55,000 feet, however, is higher than for the lower altitude intervals. This reversal in the pattern of decreasing gust frequency with increasing altitude is due to the inclusion of the two areas of moderately rough air encountered at 52,000 feet over Japan, as previously discussed. In figure 4(b), the gust frequencies for the various altitude intervals again are given based on the combined data sample but with the two areas of rough air encountered over Japan omitted. With this omission, the results indicate a significant and orderly decrease in the gust frequency with increasing altitude for the altitude range (20,000 to 55,000 feet) covered by the data.

Percent of Flight Distance in Rough Air

The percent of the flight distance which was in rough air (clear-air turbulence) is presented in figure 5 by 5,000-foot altitude intervals between 20,000 and 55,000 feet. The results show that for the higher altitudes (40,000 to 55,000 feet) rough air was generally encountered during less than two percent of the flight distance. A slightly higher percentage of rough air is indicated, however, between 50,000 and 55,000 feet over Japan. Each set of data in figure 5 shows a peak between 30,000 and 35,000 feet in the variation of the percent of rough air with altitude. This rough air is, however, of relatively low intensity, as is indicated in figure 4. The increase in the amount of rough air is probably due to the high winds and wind shears associated with jet streams which are normally prevalent at altitudes from 30,000 to 40,000 feet for the midlatitude areas covered by the data (refs. 8 and 9). In this altitude interval, the percent of flight distance in rough air over the United States and Japan appears to be significantly higher than for the other two geographic areas.

The present results on the variation in the percent of flight distance in rough air with altitude based on the combined data samples are compared in figure 6 with the estimates given in reference 3 and the more recent estimates given in reference 4. Inspection of figure 6 shows that the estimates in reference 4 are in better agreement with the present data than are the earlier results from reference 3. In particular, the results in reference 4 give a better representation of the peak in the amount of rough air between 30,000 and 35,000 feet and the decreased amount of rough air above 40,000 feet.

Size of Turbulent Areas

The probability distributions of the horizontal extents, or lengths, of the turbulent areas encountered in each area of operation are given in figure 7. The curves in this figure show the probability that the length of a turbulent area will exceed a given value. Inspection of the results shows that the probability decreases rapidly with increasing length. The results indicate, for example, that less than 50 percent of the turbulent areas exceeded 10 miles in length and, except for the operation over Japan, only about 1 percent exceeded 30 miles in length. In addition, it may be noted that turbulent areas 150 to 200 miles in length were encountered over Japan, whereas the maximum lengths for the other operations were less than 50 miles.

CONCLUDING REMARKS

Measurements of atmospheric turbulence by use of airplane-borne instruments have been obtained during research flights of Lockheed U-2 airplanes to altitudes of 55,000 feet over four geographic areas: Western United States, England and Western Europe, Turkey, and Japan. The four combined data samples cover approximately 150,000 miles of flight and represent the first extensive measurements of turbulence up to this altitude. An analysis of these data has provided information on the variation of the intensity and amount of turbulence with altitude. The results of the analysis have indicated that turbulence is generally both less severe and less frequent at high altitudes (40,000 to 55,000 feet) than at the lower altitudes. From the overall viewpoint, the data reflect an orderly decrease in the turbulence intensity with increasing altitude. A notable exception to this pattern appears to exist over Japan, however, where on two occasions large areas of moderately heavy turbulence were encountered at altitudes of approximately 52,000 feet. In both of these instances, the turbulence appeared to have been associated with the strong character of the jet stream and with a mountain-wave phenomenon over the Japanese islands.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., January 21, 1959.

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TABLE I.- SCOPE OF DATA SAMPLES

Geographic area	Number of flights	Total flight miles	Dates of record collection
Western United States	24	39,839	May 1956 to March 1957
Western Europe	87	60,514	May 1956 to Oct. 1957
Turkey	23	15,665	Nov. 1956 to June 1957
Japan	23	32,617	May 1957 to Feb. 1958

TABLE II.- DISTRIBUTION OF FLIGHT MILES BY ALTITUDE

FOR FOUR GEOGRAPHIC AREAS OF OPERATION

Altitude, ft	Flight miles for area of -				Combined data
	Western United States	Western Europe	Turkey	Japan	
20 to 25 × 10^3	695	3,153	333	890	5,071
25 to 30	508	3,754	451	602	5,315
30 to 35	609	3,263	693	698	5,263
35 to 40	821	5,632	978	1,172	8,603
40 to 45	1,358	6,316	1,152	1,421	10,247
45 to 50	5,604	10,528	4,497	4,642	25,271
50 to 55	30,244	27,868	7,561	23,192	88,865
Total flight miles	39,839	60,514	15,665	32,617	148,635

TABLE III.- FREQUENCY DISTRIBUTIONS OF DERIVED GUST VELOCITY FOR FOUR GEOGRAPHIC AREAS OF OPERATION

Derived gust velocity, U_{de}, fps	Frequency distributions for area of -				Combined data
	Western United States	Western Europe	Turkey	Japan	
2 to 3	363	625	142	864	1,994
3 to 4	112	265	62	444	883
4 to 5	48	80	14	246	388
5 to 6	19	29	3	133	184
6 to 7	16	19		102	137
7 to 8	4	6		58	68
8 to 9	2	3		28	33
9 to 10	1			23	24
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
18 to 19				0	0
19 to 20				0	0
20 to 21				1	1
Total	568	1,027	221	1,927	3,743
Miles of flight in rough air . .	753	1,276	241	1,545	3,815
Total flight miles	39,839	60,514	15,665	32,617	148,635

TABLE IV.- FREQUENCY DISTRIBUTION OF DERIVED GUST VELOCITY BY ALTITUDE FOR FOUR GEOGRAPHIC AREAS OF OPERATION

Derived gust velocity, U_{de}, fps	Frequency distributions at altitudes, ft, of -																			
	20 to 30×10^3					30 to 40×10^3					40 to 50×10^3					50 to 55×10^3				
	[a] US	[b] E	[c] T	[d] J	Combined data	[a] US	[b] E	[c] T	[d] J	Combined data	[a] US	[b] E	[c] T	[d] J	Combined data	[a] US	[b] E	[c] T	[d] J	Combined data
2 to 3	142	230	15	54	441	83	212	28	103	426	18	92	85	31	226	120	91	14	676	901
3 to 4	41	85	2	20	148	13	91	8	29	141	1	58	38	13	110	57	31	14	382	484
4 to 5	16	33		6	55	4	23	2	15	44		12	12	5	29	28	12		220	260
5 to 6	8	12		3	23	1	9	1	2	13		5	2		7	10	3		128	141
6 to 7	6	5		1	12	1	5		2	8		5			5	9	4		99	112
7 to 8	1	2		1	4		2			2		2			2	3	0		57	60
8 to 9	1	2			3											1	1		28	30
9 to 10	0				0											1			23	24
10 to 11	1				1											0			13	13
11 to 12	0				0											1			6	7
12 to 13	1				1														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	217	369	17	85	688	102	342	39	151	634	19	174	137	49	379	230	142	28	1,642	2,042
Miles of flight in rough air . .	114	317	5	151	587	216	472	52	262	1,002	57	239	138	74	508	366	248	46	1,058	1,743
Total flight miles	1,203	6,907	784	1,492	10,386	1,430	8,895	1,671	1,870	13,866	6,962	16,844	5,649	6,063	35,518	30,244	27,868	7,562	23,192	88,865

[a]US Western United States.
[b]E Western Europe.
[c]T Turkey.
[d]J Japan.

TABLE V.- FREQUENCY DISTRIBUTIONS OF DERIVED GUST VELOCITY FOR OPERATIONS OVER JAPAN

Derived gust velocity, U_{de}, fps	Frequency distributions for -		
	Total sample (23 flights)	Flight CW-58-2	Flight CW-58-4
2 to 3	864	396	120
3 to 4	444	255	65
4 to 5	246	173	31
5 to 6	133	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	0
16 to 17	3	3	0
17 to 18	0	0	0
18 to 19	0	0	0
19 to 20	0	0	0
20 to 21	1	1	0
Total	1,927	1,161	237
Miles of flight in rough air . .	1,545	151	196

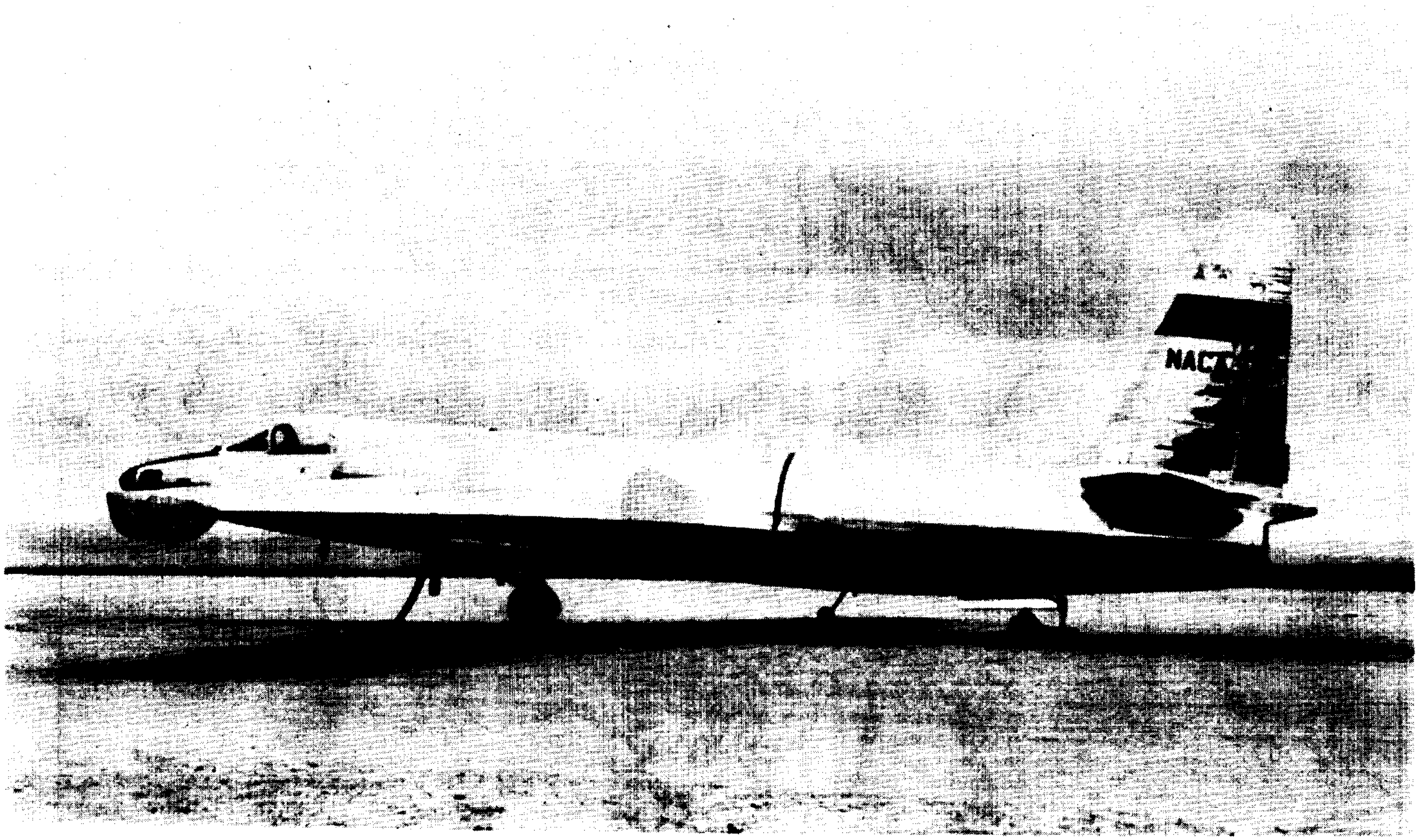


Figure 1.- Test airplane. L-57-96

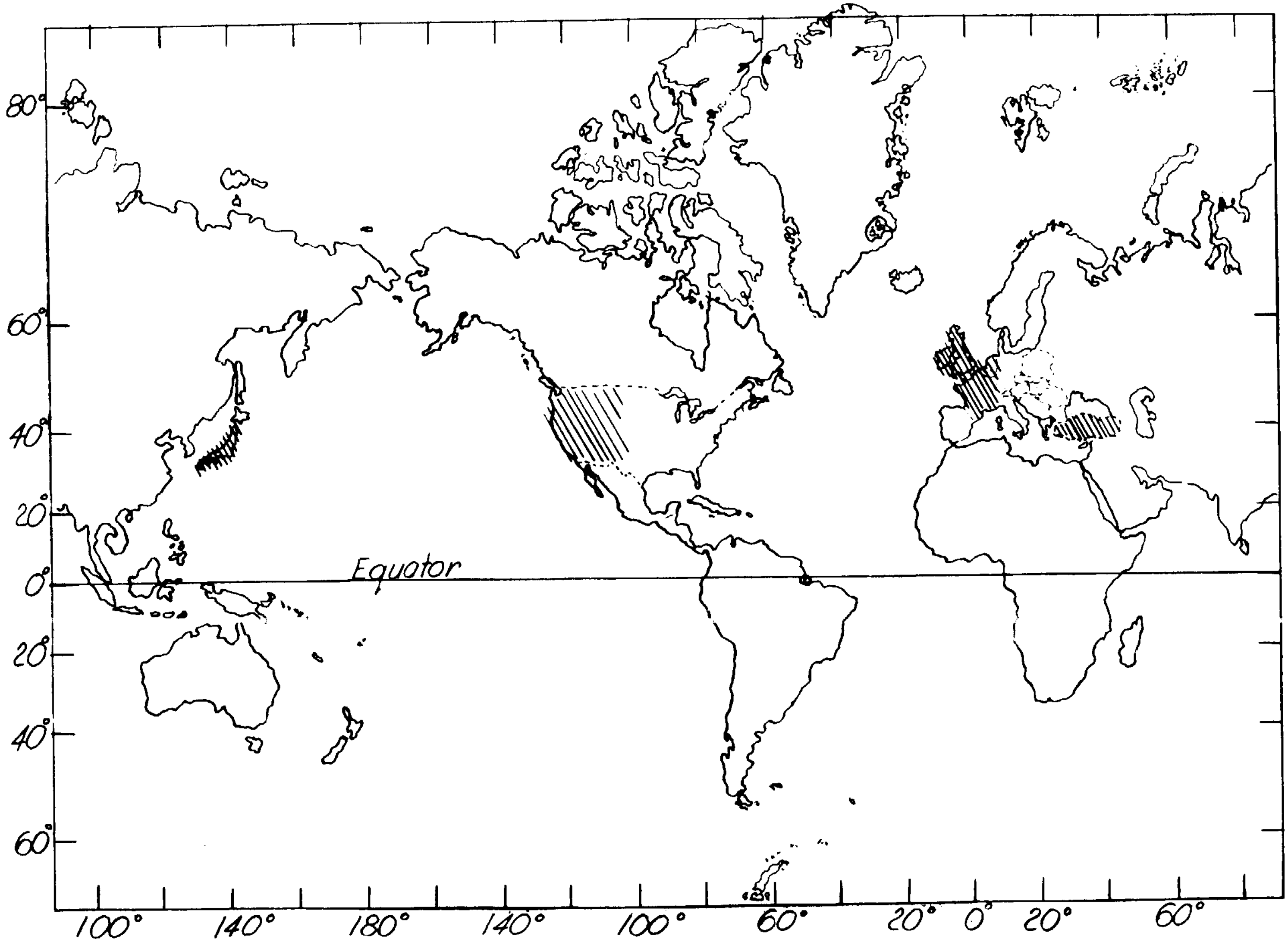
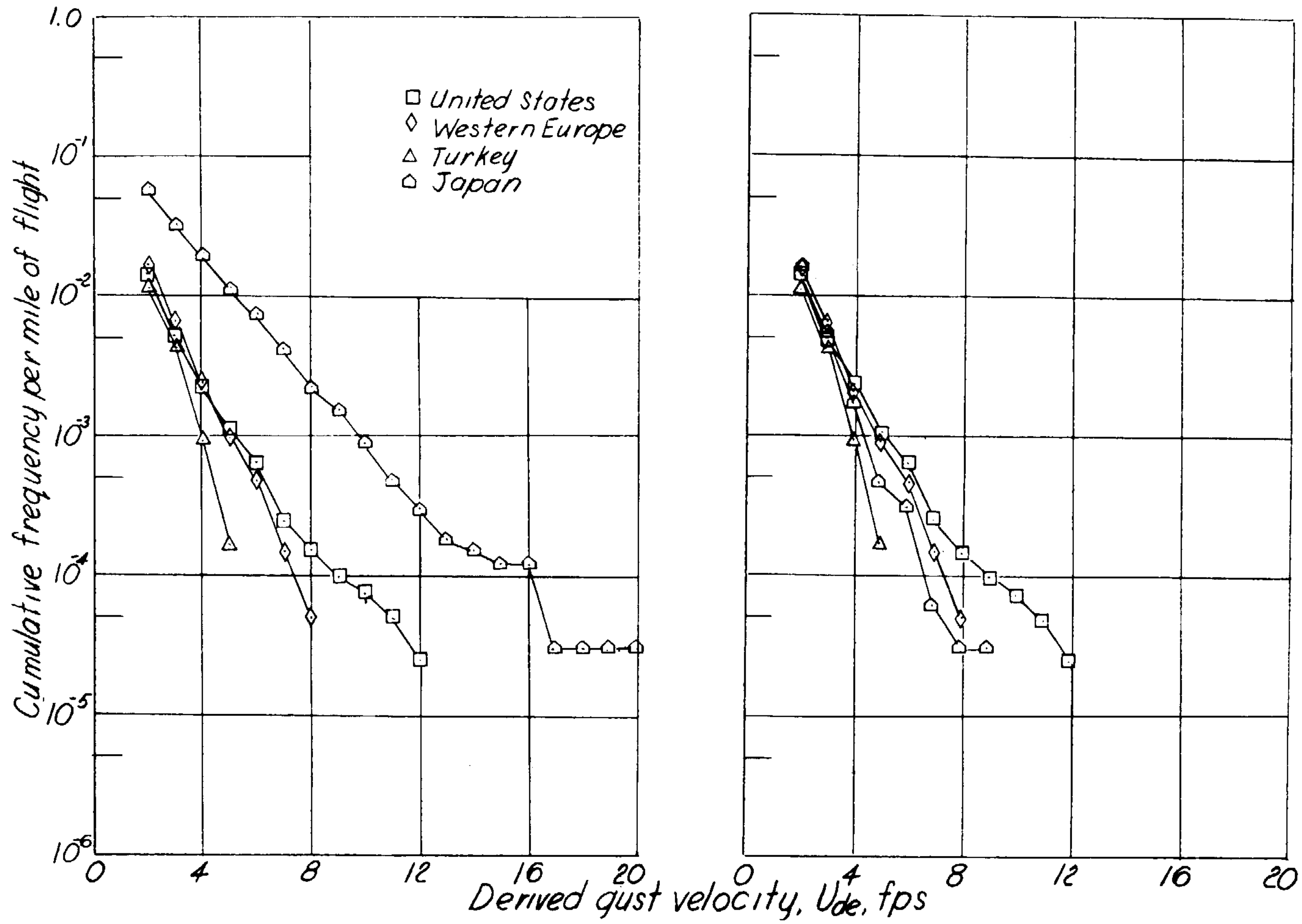
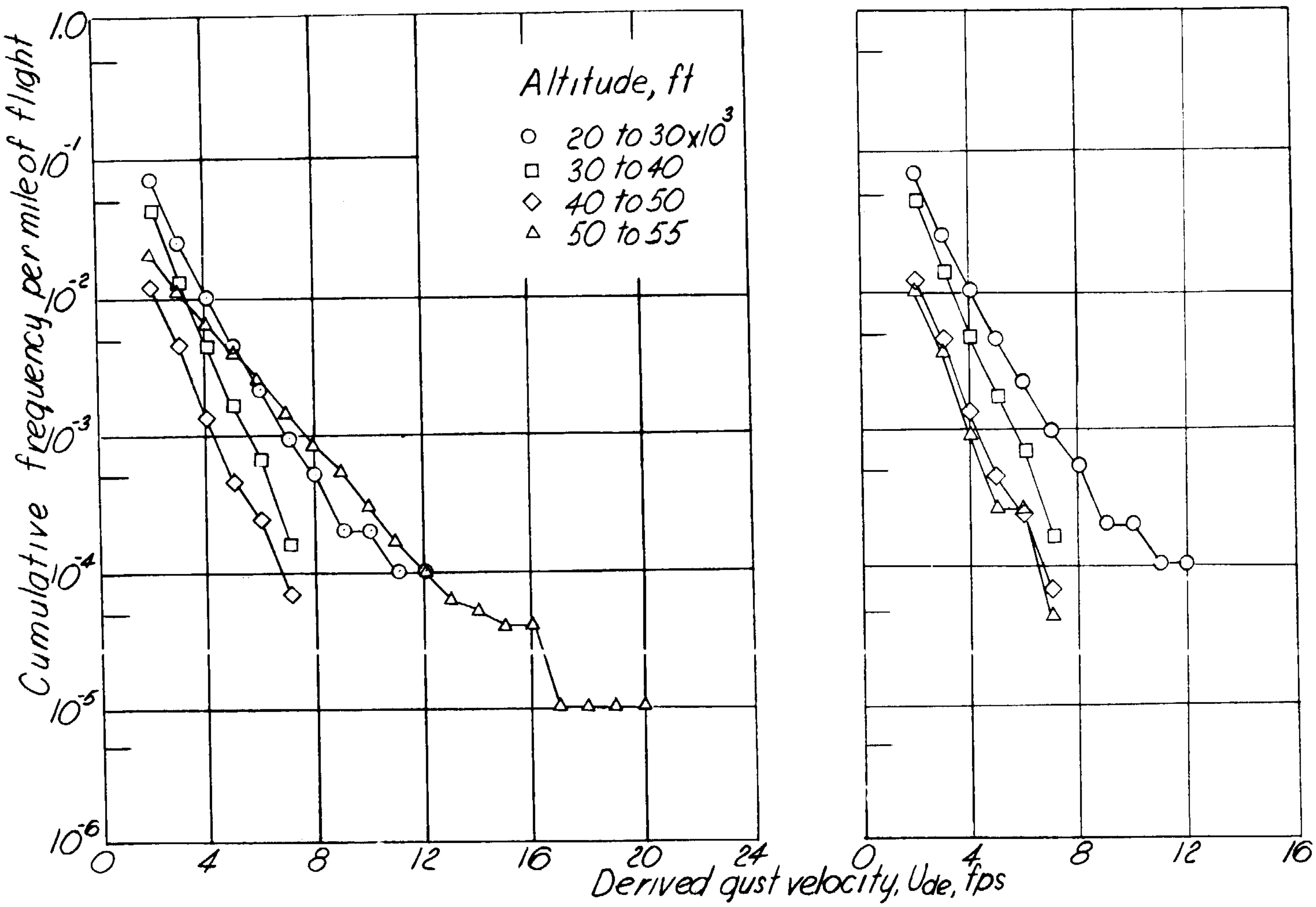


Figure 2.- Geographic areas (shown cross-hatched) sampled during four operations.



(a) All data. (b) Flights CW-58-2 and CW-58-4 omitted.

Figure 3.- Frequency of exceeding given values of gust velocity per mile of flight for four geographic areas.



(a) All data.

(b) Flights CW-58-2 and CW-58-4 omitted.

Figure 4.- Cumulative frequency distributions per mile of flight for various altitude intervals.

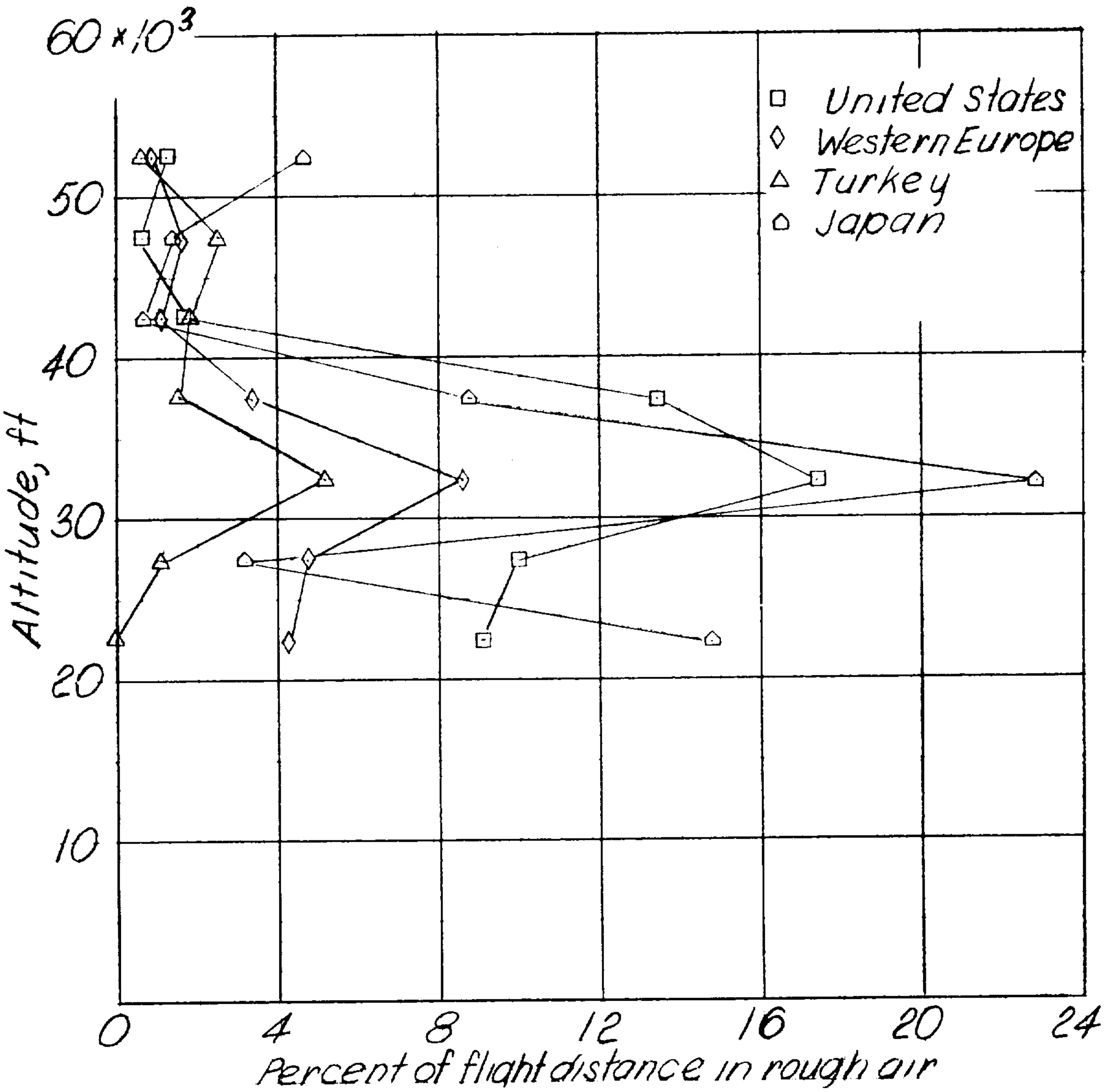


Figure 5.- Percent of flight distance in rough air (clear-air turbulence) at various altitudes for four geographic areas of operation.

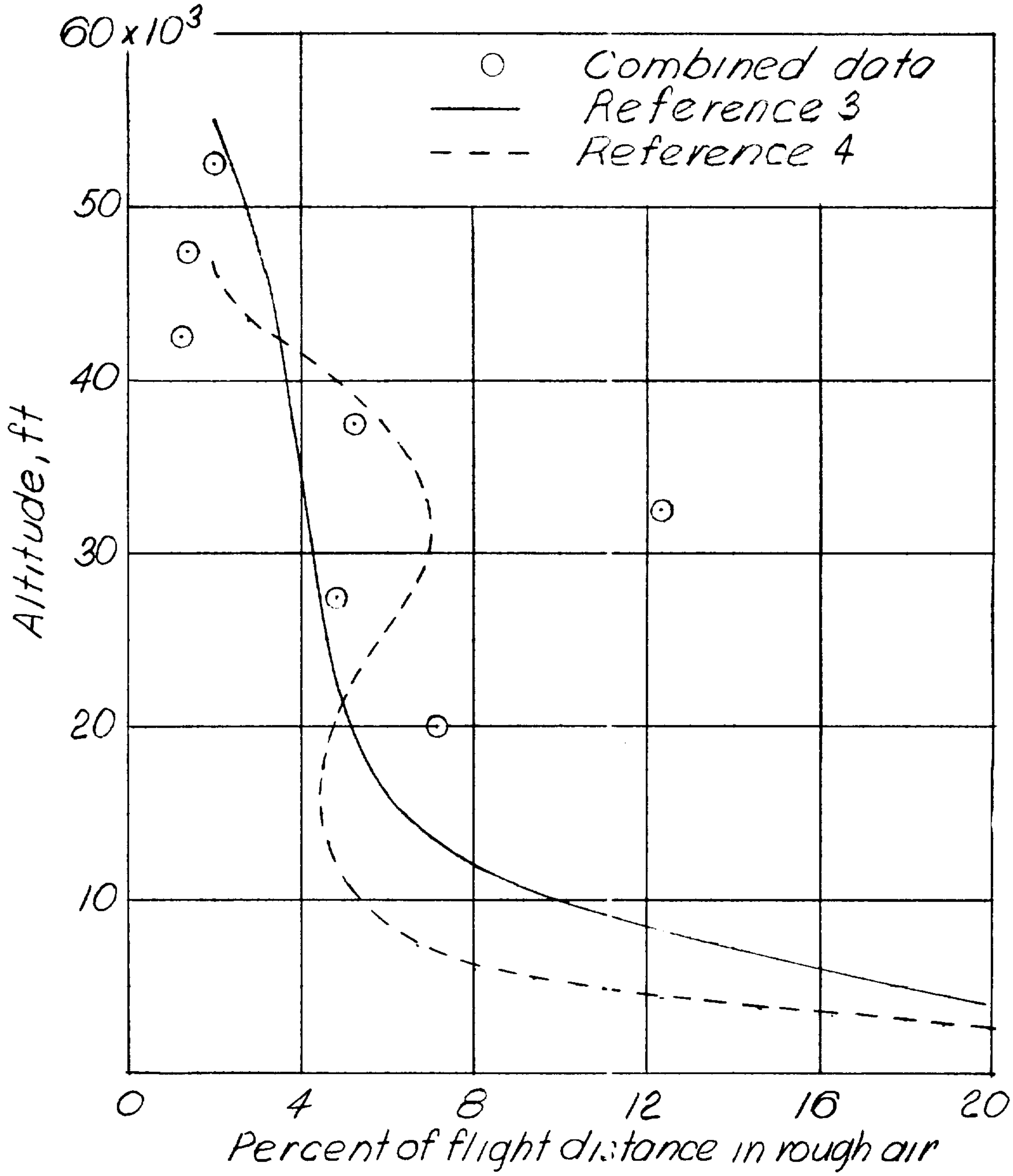


Figure 6.- Comparison of percent of flight distance in rough air at various altitudes.

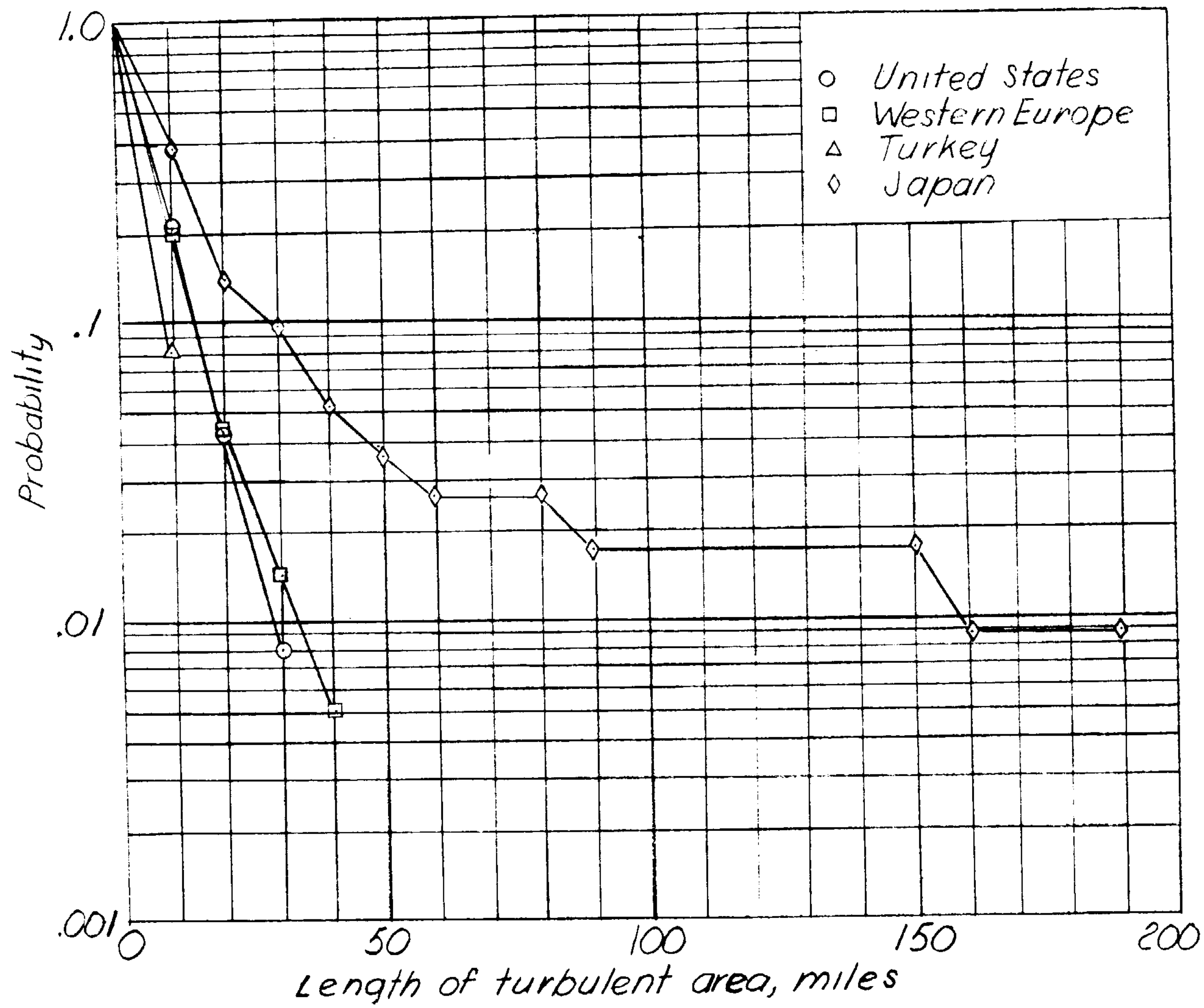


Figure 7.- Probability that length of turbulent area will exceed a given value.