PUBLICITY

NACA-AWS UPPER ATMOSPHERE
RESEARCH PROGRAM

PRIMARY VEHICLE
LOCKHEED U-2

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

1512 H Street, N.W. Washington 25, D.C.

FOR RELEASE
MONDAY, MAY 7, 1956

NACA ANNOUNCES START OF NEW RESEARCH PROGRAM

The need for more detailed information about gust-meteorological conditions to be found at high altitude, as high as 50,000 feet, has resulted in the inauguration of an expanded research program to provide the needed data, Dr. Hugh L. Dryden, Director of the National Advisory Committee for Aeronautics, announced today.

"Tomorrow's jet transports will be flying air routes girdling the earth", Dr. Dryden said. "This they will do at altitudes far higher than presently used except by a few military aircraft. The availability of a new type of airplane, which is one of several that will be used in the program, helps to obtain the needed data in an economical and expeditious manner."

The new airplane, the Lockheed U-2, is powered by a single Pratt & Whitney J-57 turbojet engine and is expected to reach 10-mile-high altitudes as a matter of routine, according to the NACA. A few of the Lockheed airplanes are being made available for the expanded NACA program by the USAF.

The program is along lines recommended by the Gust Loads Research Panel of the NACA's technical Subcommittee on Aircraft Loads. In its research programs, the NACA is charged with coordination of aeronautical research, and with taking action necessary to avoid undesirable duplication of effort.

Among specific research goals will be more precise information about clear air turbulence, convective clouds, wind shear, and the jet stream. Richard V. Rhode, Assistant Director for Research of the NACA, said that as a result of information so to be gained, tomorrow's air travelers might expect a degree of speed, safety and comfort beyond present hope of the air transport operators.

"The program would not have been possible," Mr. Rhode said, "without the ability of American scientific effort to join forces."

Actually, according to Mr. Rhode, success of the program depends in large degree upon the logistical and technical support which the Air Weather Service of the USAF will be providing. USAF facilities overseas will be used as the program gets underway, to enable gathering research information necessary to reflect accurately conditions along the high-altitude air routes of tomorrow in many parts of the world. The data gathering flights will also be used, at the request of the USAF, to obtain information about cosmic rays, and the concentration of certain elements in the atmosphere including ozone and water vapor.

The first data, covering conditions in the Rocky Mountain area, are being obtained from flights made from Watertown Strip, Nevada. Mr. Rhode noted that the data would be equally useful to technical experts of the Air Weather Service in expanding their knowledge of atmospheric conditions at high altitude.

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HEADQUARTERS
AIR WEATHER SERVICE
MILITARY AIR TRANSPORT SERVICE
UNITED STATES AIR FORCE
WASHINGTON 25, D.C.

EXTRACT FROM AWS SCIENTIFIC SERVICES NEWSLETTER JUNE 1956

Air Weather Service Support of NACA Program

AWS is giving its support to the NACA atmospheric-research program which was initiated some weeks ago and announced on 7 May by Dr. Hugh L. Dryden, the Director of NACA. Early in 1956 the NACA began planning for an atmospheric-research program of broad interest to U.S. aeronautical science, both civilian and military. Observations from various points in the Northern Hemisphere will enable an integrated study of high-altitude phenomena. The Lockheed built U-2 aircraft, capable of collecting data at altitudes between 50,000 and 55,000 feet, is being used as the primary test bed in the NACA program. The main objective of NACA's program is the gathering of data on turbulence associated with the jet stream and with convective clouds, wind structure, and temperature at jet levels, cosmic ray effects etc.

NACA's program has already been launched in the U.S. and was recently initiated in the European Theater. Since NACA does not have independent facilities for conducting test programs abroad, the overseas program will be based at USAF installations and supported logistically by appropriate USAF commands.

The 1st Weather Reconnaissance Squadron, Provisional, activated by AWS and rendering direct support to the NACA program has been established in the U.K. The weather reconnaissance conducted therefrom will be aimed at collecting high-level data on jet streams associated with higher latitudes, data characteristics of the northern side of the westerlies, and weather information associated with the blocking patterns of northern Europe. The 2nd Weather Reconnaissance Squadron, Provisional, has been activated at Watertown, Nevada, within easy flying range of areas where maountain waves are clearly defined, and relatively frequent.
This squadron later will relocate at another site, yet to be selected, at which a different variety of meteorological situations prevail. The location will probably be at a lower latitude, where the more southerly areas of the westerlies can be probed and where data from different kinds of weather patterns can be secured for synoptic research. Still different locations may be utilized since it is desired that the upper levels of the widest possible variety of synoptic situations be explored with the U-2 data-gathering system.

AWS has a very strong interest in the NACA program and the data it will produce. Throughout its history the Air Weather Service has had to operate under a heavy and unique handicap. Its position has been one of having to forecast, and otherwise to provide weather service, for aircraft operations at flight altitudes where weathermen previously had little observational and no forecasting experience. Not only did our meteorologists not know how to provide much needed forecasts, but also they had no way of knowing what the critical weather problems were at the new altitudes being probed operationally by faster and higher flying aircraft. Further, our weather science had not even developed the instruments required for adequate measuring of the meteorological elements in the rarified environments. Early in 1955, in a letter addressed to General Power, Commanding General of ARDC, General Moorman put this deficiency on record and requested General Power's assistance in lifting AWS off the "horns of its dilemma".

Concurrently, the NACA's Gust Loads Research Panel had under study the requirements for an expanded program of turbulence-data collection. The new NACA program now underway is designed to satisfy not only its own requirements but those of the AWS as well. Many of the data gathered will be forwarded to the Geophysical Research Directorate of ARDC to assist them in developing methods of forecasting meteorological phenomena which are important to high altitude flight; some of the data will be processed and analyzed by NACA to form the basis for statistical studies of turbulence.

a. The U-2 and its Weather-Instrumentation System.

Many of the data are recorded on the KS-4 Aerograph System which is designed to receive atmospheric-measurement inputs and to indicate the values both visually and graphically. The system can record six functions, five graphically and one numerically, in different colors on a continuous-roll paper chart. The recording equipment and other instrumentation (described below) were provided by NACA and the Wright Air Development Center.

b. Basic Meteorological Measurements.

Free-air temperature is measured by the ML-470/AMQ-8 vortex thermometer system which was developed by the Naval Research Laboratory to measure temperatures with an accuracy of $1/2^{o}$C at airspeeds up to 500 knots. The indicated free-air temperature and relative humidity are also measured by the AN/AMQ-7 temperature-humidity measuring system which was developed for AWS by the Evans Signal Laboratory at Belmar, N.J. Here, a precision thermistor measures the temperature and a new type of carbon strip measures the relative humidity. Pressure altitude is measured by a precision pressure transducer, and airspeed is measured by an airspeed transducer. The airspeed, pressure altitude, relative humidity, and two temperature measurements are recorded graphically on the KS-4 System. The magnetic heading measured by a gyrosyn compass is fed into the KS-4 and recorded on the paper roll in the form of a series of numbers. Winds are computed from: 1) the headings and airspeed automatically printed on the KS-4, and 2) the drift and groundspeed data recorded manually by the pilot from use of his driftmeter.

c. Special Meteorological Measurements.

A NACA developed VGH recorder includes two pressure sensitive elements for continuous measurement of airspeed and pressure altitude, a galvanometer for measuring the output of a remote acceleration transmitter, and a timing mechanism. Motion of each element is amplified by rotation of a mirror which, in turn, moves a reflected lamp image across a 200 ft. roll of 70 mm photographic paper. Also installed is a sensitive airspeed recorder which is similar to the VGH recorder except that a higher sensitivity factor for airspeed is obtained by use of multiple mirrors on the airspeed pressure element. The NACA, further, has provided a VG recorder that traces the upper envelope (or peak values) of accelerations as a function of airspeed on a smoked glass plate which is ready for inspection immediately after completion of a flight. Finally, the NACA has provided for installation of a turn-meter oriented to record the rate of pitch of the aircraft; the meter records optically on a 50-ft roll of sensitized paper.

A new turbulence recorder developed by WADC, the Flight Recorder Model BB, continuously records the indicated airspeed, pressure altitude, and normal acceleration on arc-sensitized paper. The record from this instrument is immediately available for inspection after flight of the aircraft.

d. Equipment and Measurements for the Future.

Not only does the U-2 provide us with a platform from which badly needed high altitude meteorological data can be secured, but it also gives us the opportunity to test certain new light-weight types of meteorological instrumentation. The tests, furthermore, will have the advantage of having been conducted under operational environment. Contemplated for tests, as soon as current basic development work is completed at WADC, are an infrared hygrometer for accurate measurement of dewpoint, an improved vortex temperature probe, a vortex psychrometer for measuring free-air temperature and relative humidity, a means of measuring visibility, and improved turbulence measuring and recording equipment.

e. Significance of Data Produced by the NACA Program.

Crews of the new B-52 bomber have furnished disturbing reports of turbulence at high altitudes. Military operations such as bombing, photographic reconnaissance, and air to air refueling are very sensitive to this meteorological phenomenon, as well as are any jet aircraft flights made near the "coffin corner". As to contrails, these artificially produced clouds remain of great importance to high flying aircraft from the detection stand-point. To learn how to forecast them for the aircraft of the future we need direct observations of these two phenomena, in conjunction with measurements of temperature, humidity, and possibly other meteorological elements.

What about high-level layers of haze or very thin cloud formations invisible from the ground but of great significance whenever aircraft are near each other at these altitudes? We must have more experience with these things before we can learn how to predict them satisfactorily. Encounters of the U-2 with high level obstructions to visibility, and with contrails are recorded by the pilot for comparison with other measurements made by the meteorological instrumentation system and with synoptic data.

We suspect that very fast flying high altitude aircraft will begin to discover brand-new problems which relate to meteorological and other geophysical phenomena. Fluctuations in air temperature and density may be critical at times with respect to aircraft skin temperatures and engine performance. Various types of radiation present at high levels may be important to crews and equipment. Ozone may have unexpected effects. To become aware of the problems and to find out how to solve them require actual experience with the phenomena together with collections of data to help us state the solutions in quantitative form.

Even from the point of view of indirect effects on Air Force operations high level weather reconnaissance demonstrates its importance. Many meteorologists long have felt that ozone is important for a really complete synoptic analysis. Occurrences such as Scherhag's "Berlin warming", in which he recorded phenomenal 24-hour temperature changes in the stratosphere over Berlin, undoubtedly are associated with important synoptic changes at other heights, latitudes and longitudes. Kochanski's wintertime polar jet which he discovered through study of meager radiosonde data, and possibly other air currents at very high altitudes, could be of both indirect and direct operational concern to the Air Force. For proper diagnosis and prognosis of these phenomena, high altitude weather aircraft observations are essential.

We have high hopes that the NACA program will furnish us with data enabling us to at least "get the jump" on the operational aircraft of the near future. The outlook is promising!

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

1512 H Street, N.W. Washington 25, D.C.

FOR RELEASE JULY 9, 1956

High Altitude Research Program Proves Valuable

Initial data about gust-meteorological conditions to be found at 10-mile-high altitudes which have been obtained to date by the relatively few flights of Lockheed U-2 airplanes have already proved the value of the aircraft for this purpose, Dr. Hugh L. Dryden, Director of the National Advisory Committee for Aeronautics, said today.

"The airplane has shown its capability to climb to 50,000 feet and maintain that altitude for the time necessary to obtain the research information desired," Dr. Dryden said. "Further, it has adequate load capacity to accommodate the data-gathering instrumentation required."

Research flights covering the western part of the United States are being made from Watertown Strip, Nevada. Within recent weeks, preliminary data-gathering flights have been made from an Air Force base at Lakenheath, England, where the Air Weather Service of the USAF is providing logistical and technical support. As the program continues, flights will be made in other parts of the world.

Among specific research goals are more precise information about clear air turbulence, convective clouds, wind shear, and the jet stream. In addition, information about cosmic rays, and the concentration of certain elements in the atmosphere including ozone and water vapor, is being gathered at the request of the USAF. It is expected that considerable time will elapse before sufficient information, covering all subjects of interest, has been obtained and reduced to useful form.

The instrumentation carried by the U-2 airplane includes special equipment furnished by the Wright Air Development Center, and the National Advisory Committee for Aeronautics.

Turbulence data is being recorded on the following specially developed instruments furnished by Wright Air Development Center and the National Advisory Committee for Aeronautics:

1. A VGH recorder developed by the NACA contains two pressure sensitive elements for continuously measuring indicated airspeed and pressure altitude, a galvonometer element for measuring the output of a remote acceleration transmitter and a timing mechanism. Each element causes rotation of a mirror which in turn moves a reflected lamp image across the recording medium. Recording is affected on a 200 foot roll of 70 mm photographic paper;

2. A sensitive airspeed recorder similar to the VGH recorder except that a high sensitivity factor for airspeed is obtained by use of multiple mirrors on the airspeed pressure element;

3. A NACA VG recorder that scribes an envelope of acceleration against airspeed on a smoked glass plate. This record is immediately ready for inspection following flight;

4. A NACA turn meter that records optically on a 50-foot roll of 2-7/16'' photographic film. This meter is oriented so as to record the airplane's rate of pitch;

5. A new turbulence recorder developed by Wright Air Development Center, ''Flight Recorder Model BB'' continuously records indicated airspeed, pressure altitude and normal acceleration on arc-sensitized paper. The record of this instrument is immediately available for inspection following a flight.

Improved equipment to be added as soon as development work currently is completed, will include an infra-red hygrometer for accurate measurement of dew point, an improved vortex temperature probe, a vortex psychrometer for measuring true free air temperature and relative humidity, a means of measuring visibility and improved turbulence measuring and recording equipment.

True free air temperature is being measured by a vortex thermometer system ML-470/AMQ-8 that was developed by the Naval Research Laboratory to measure true free air temperature with an accuracy of one half degree celsius. Air flows through a corkscrew type spinner vane that creates a vortex, cooling the air at the center of the vortex by an amount equal to the dynamic heating for that flight speed. The temperature at the center of the vortex will then be equal to ambient temperature. A precision wire wound resistance temperature element is located in the center of the vortex. This temperature measuring system has been tested on a whirling arm and found to have an accuracy of better than one half degree celsius at speeds up to 500 knots.

Indicated free air temperature and indicated relative humidity are being measured by temperature-humidity measuring set AN/AMQ-7. The system was developed for the Air Weather Service by the Evans Signal Laboratory at Belmar, New Jersey. It has a recovery factor of about .87 and has a precision thermistor for measuring temperature and a carbon strip for measuring humidity. The carbon strip is a new element that consists of a humidity sensitive carbon coating which changes in resistance as the humidity changes.

Pressure altitude is measured by a precision pressure transducer that furnishes an electrical signal to an aerograph recorder. Air speed is measured by an airspeed transducer.

The AN/AMQ-7 temperature-humidity measuring system and the AN/AMQ-8 vortex thermometer have been modified to connect their electrical output into the KS-4 Aerograph system for automatic recording.

The KS-4 Aerograph system is designed to receive data inputs of atmospheric measurements and to indicate these values both visually and graphically. It is capable of recording six functions, five graphic and one numerical. Each graphic recording channel consists of a complete servo mechanism which positions a stylus on a lead screw in proportion to the electrical angle of a transmitting synchro. The servo mechanism consists of a two-phase motor, a synchro lead screw and stylus and suitable gearing. The printed material is impressed on the chart by action similar to that of a typewriter, by tapping the paper through an inked ribbon. Each recorded value has its own particular color and the ribbon is automatically advanced and oscillated laterally so as to make full use of the width of the ribbon.

The magnetic heading measured by the gyrosyn compass is fed into and automatically printed in numerical form by the KS-4 Aerograph.

Winds are computed from headings and airspeeds recorded on the KS-4 Aerograph and drift and ground speed data recorded by the pilot from the driftmeter.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

FOR RELEASE FEBRUARY 11, 1957

The Lockheed U-2 shown here, is being used by the National Advisory Committee for Aeronautics, to obtain detailed information about gust-meteorological conditions at high altitude. The research program makes use of instrumentation furnished by the NACA and the Wright Air Development Center of the USAF, and logistical and technical support is provided by the Air Weather Service of the USAF. Since the program began last spring, numerous data gathering flights have been made in the United States and elsewhere in the world. The NACA has found the U-2 (powered by a Pratt and Whitney J-57) a most useful research tool, especially because of its capability to maintain flight at high altitude, as high as 55,000 feet. Subjects under study include clear air turbulence, convective clouds, and the jet stream.

LAL-57-96 and LAL-57-97

NACA
LAL 57-97

Lockheed U-2 airplane used by NACA for gust-meteorological studies at high altitude.

Approved For Release 2004/05/13 : CIA-RDP90T00782R000100040001-9

NACA
LAL 57-96

Lockheed U-2 airplane used by NACA for gust-meteorological studies at high altitude.

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RESEARCH MEMORANDUM

PRELIMINARY MEASUREMENTS

OF ATMOSPHERIC TURBULENCE AT HIGH ALTITUDE AS

DETERMINED FROM ACCELERATION MEASUREMENTS ON

LOCKHEED U-2 AIRPLANE

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

PRELIMINARY MEASUREMENTS OF ATMOSPHERIC TURBULENCE AT HIGH ALTITUDE AS DETERMINED FROM ACCELERATION MEASUREMENTS ON LOCKHEED U-2 AIRPLANE

By Thomas L. Coleman and Jack Funk

SUMMARY

An analysis of a sample of turbulence data obtained from VGH records taken on Lockheed U-2 airplanes during research flight up to 55,000 feet over England and Western Europe has indicated substantial reductions in the number and intensity of gusts with increasing altitude. These results on the variation of atmospheric turbulence over England and Western Europe were found to be in overall agreement with previous turbulence data obtained from airplane- and balloon-borne instruments over the United States.

INTRODUCTION

The collection of detailed information at high altitudes on atmospheric turbulence and other meteorological conditions has, in the past, been largely dependent upon the availability of operational airplanes. As a consequence, the collection of such data has, in general, lagged behind the development of airplane altitude capabilities. To the present time, the available airplane measurements of atmospheric turbulence have been almost entirely limited to flight altitudes below approximately 45,000 feet. For higher altitudes, the only information available is some measurements obtained by means of balloon-borne instruments. (See ref. 1.) These measurements have provided limited information on turbulence variations with altitudes to approximately 60,000 feet. In addition to the altitude limitations of the foregoing investigations, the measurements were also limited in regard to geographic areas and were largely confined to continental United States. This lack of information on high-altitude turbulence conditions around the world has been a handicap in aircraft design studies and in operational analysis, both in regard to aircraft load problems and in regard to stability and control problems.

During the early part of 1956, the National Advisory Committee for Aeronautics, in cooperation with the Air Weather Service of the United States Air Force, initiated a research program aimed at providing detailed meteorological information both at higher altitudes than those covered by present-day operating airplanes and for various geographic areas of the world. The availability of Lockheed U-2 airplanes at the initiation of this program permitted the coverage of flight altitudes to approximately 55,000 feet. The NACA activity in this program has so far been primarily aimed at obtaining information on the amount and intensity of atmospheric turbulence at these higher altitudes. The Air Weather Service has simultaneously provided instrumentation to collect data on humidity, pressure variations, and winds.

The initial research flights of the U-2 airplane were undertaken to cover two geographic areas, the United States and Western Europe. Because of operational difficulties, a statistically significant sample was initially obtained only from the operations over England and Western Europe. For these operations, measurements covering a total of 22,000 flight miles were made and evaluated. Although this sample is small, the initial results appear to be of sufficient interest to warrant publication. Accordingly, these results are presented herein and are compared with the earlier estimates on the variation of atmospheric turbulence with altitude given in reference 1.

INSTRUMENTATION AND SCOPE OF DATA

The flight measurements were obtained during flights of several Lockheed U-2 airplanes for the high-altitude meteorological research program of the NACA in cooperation with the Air Weather Service. The Lockheed U-2 is a subsonic, straight wing, single-engine airplane originally designed for use as a high-altitude test medium for engine and aircraft-component testing. The high-altitude performance and economy of operation of the U-2 airplane were the prime factors affecting its selection for use in the present research program.

The measurements pertinent to this report consisted in time-history records of airspeed, acceleration, and pressure altitude taken with NACA VGH recorders (ref. 2). The time histories were recorded on photographic paper moving at 8 inches per minute. Records were obtained on 17 flights during operations from bases at Lakenheath, England, and Wiesbaden, Germany, between May and September 1956. The flight plans used in the operations consisted in climbing to an altitude of approximately 45,000 feet, cruising initially at approximately 45,000 feet with the altitude gradually increasing to approximately 55,000 as the fuel load decreased, and then descending to the home base. For these initial operations, the flight schedules were based primarily on airplane availability, and no attempt was made to schedule flights to sample turbulence associated with specific meteorological conditions. The turbulence encountered during the present operations was, for the most part, in clear air, and no turbulence in heavy cumulus clouds or thunderstorms is represented in these data.

The scope of the data in terms of miles flown within different altitude intervals is summarized in the following table:

Pressure altitude, ft	Flight miles
20,000 to 30,000	1,548
30,000 to 40,000	3,492
40,000 to 50,000	6,021
50,000 to 55,000	10,461
Total	21,522

Because of the operational procedures used, only a small amount of information was obtained at the lower altitudes; consequently, only the data above an altitude of 20,000 feet are included in this paper.

EVALUATION OF DATA

The VGH records were evaluated to obtain the vertical gust velocities, the percent of rough air at various altitudes, and the horizontal extent of the turbulent areas encountered. The evaluation procedures are similar to the procedures used in reference 1 and are discussed briefly in the following paragraphs.

The vertical gust velocities were derived from simultaneous readings of acceleration, airspeed, and altitude through the use of the gust equation which is given in reference 3 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 complete frequency counts of all gust velocities greater than 2 feet per second. Values of airspeed and pressure altitude were obtained from the records for each acceleration evaluated. The in-flight weight loss 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 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 from the airplane manufacturer.

The gust-velocity values presented herein may be open to some question because of 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.

In addition to determining the gust velocities, the VGH records were evaluated to obtain the horizontal extent of turbulent areas and the percent of rough air at the different altitudes. For the purpose of determining the horizontal extent 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 corresponds to that used in previous gust studies such as reference 1. The length of each turbulent area was found simply 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 percent of rough air for that interval.

RESULTS AND DISCUSSION

Overall Gust Distributions

The gust velocities derived from the acceleration and airspeed data are presented as frequency distributions in table I for four altitude intervals between 20,000 and 55,000 feet and are shown in figure 1 as cumulative frequency distributions per mile of total flight for each altitude interval. The cumulative distributions give the average number of gusts per mile of total flight which exceeded given values of gust velocity. Inspection of the results of this investigation in figure 1 shows that, over the altitude range covered, variations on the order of 10 to 1 exist in the frequency with which given gust velocities were encountered. In general, the distributions depict a consistent decrease in gust frequency with increasing altitude. The data for the altitudes of 30,000 to 40,000 feet deviate from this pattern to some extent, however, and indicate a lower frequency for the higher gust velocities than would be expected from the general pattern. Because of the limited sample size, this deviation from the general pattern may not be real, but due to a sampling error.

For comparison with the present data, the cumulative frequency distributions of gust velocity were determined from the results of reference 1 and these distributions are also shown in figure 1. These distributions are based on the basic distribution of non-thunderstorm turbulence and the variation of gust intensity with altitude given in figures 5 and 1, respectively, of reference 1. Comparison of the two sets of distributions in figure 1 shows that the slopes of the two sets of distributions are about the same but that, in general, the data of this investigation indicate somewhat lower gust frequencies than those obtained from reference 1. One possible reason for the lighter level of turbulence for the present data is the limited seasonal coverage, the present data covering only the summer months; whereas the results from reference 1 represent average turbulence conditions for operations throughout the year. More severe clear-air turbulence may be anticipated during seasons of the year other than summer and particularly during the winter months when the winds at high altitude are likely to be the strongest.

Intensity of Turbulence

In order to compare in further detail the gust measurements of this investigation with the results from reference 1, it is helpful to consider separately the variations in the intensity and in the amount of rough air with altitude. As an indication of the severity of the rough air alone, the cumulative frequency distributions of gust velocity per mile of flight in rough air are plotted in figure 2 for the different altitude intervals. For comparison, the corresponding gust distributions for non-thunderstorm turbulence were calculated from reference 1 and are also shown in the figure. Inspection of the present data in figure 2 shows that, in general, the gust frequency per mile of rough air also decreased with increasing altitude. However, again, the data for the altitudes of 30,000 to 40,000 feet do not follow this pattern and, in this case, indicate a lower frequency than is shown for the other altitudes. Examination of the time-history records revealed that this low gust frequency resulted mainly from two long (30 to 50 miles) areas of turbulence of low intensity. In view of the peculiarity of the data for the altitudes of 30,000 to 40,000 feet, the present indication of a low gust frequency for this altitude interval is open to question.

Comparison of the results of this investigation on the gust intensity, based on miles of flight in rough air, with the corresponding results from reference 1 shows not only that the two sets of distributions have approximately the same slopes but also that the gust intensity is considerably lower for the present data. (See fig. 2.) For a given frequency of occurrence, the gust velocities shown by the present data are, in general, only about 75 percent as large as the gust velocities given by the results from reference 1 for the same altitude interval. For the altitude of 30,000 to 40,000 feet, the percent is even lower, it being about 50 percent. Thus, in general, the intensity of the rough air for the data of this investigation is substantially lower than that given by reference 1.

In addition to the direct comparison of the gust intensities given in the preceding paragraph, it is of interest to compare the relative variations of the gust intensities with altitude for the two sets of gust distributions. In figure 3, the variations of the gust intensity with altitude for the present results and the results based on reference 1 are given in terms of the ratio of the maximum gust velocity expected in a given flight distance in rough air at the lower altitude interval (20,000 to 30,000 feet) to the maximum gust velocity for the same flight distance in rough air at higher altitudes. The data in figure 3 were obtained by determining from the gust distributions of figure 2 the maximum gust velocity expected in a given flight distance in rough air at different altitudes for each sample of data. For this purpose, a gust frequency of 0.05 per mile in figure 2 was selected as being through the more reliable range of the present distributions. The values of maximum gust velocity obtained from figure 2 for each set of distributions were then normalized to the gust velocity for the lower altitude interval in order to obtain the gust-velocity ratios plotted in figure 3.

Figure 3 shows that the relative variation of the gust intensity with altitude for the present data is in good agreement with the results from reference 1 except for the data for the altitudes of 30,000 to 40,000 feet. As previously noted, however, the reliability of the data at this altitude is open to some question. The comparison presented in figure 3 implies that the variation in gust intensity with altitude over Western Europe, at least for the summer season, is similar to that indicated in reference 1 for this country.

Amount of Turbulence

The percent of the flight distance within each altitude interval which was in rough air is presented in figure 4. Similar results, based on airplane and telemeter data from reference 1, are also given in the figure for comparison. Figure 4 shows that the results of this investigation are in good agreement with the results from reference 1 for altitudes above 35,000 feet. Below this altitude, the present data indicate slightly higher percentages of rough air than do the data from reference 1. The high percentage of rough air for the altitudes of 30,000 to 35,000 feet resulted from the two areas of 30 to 50 miles of turbulence of low intensity that were mentioned previously. Thus, in general, the amount of rough air at the various altitudes is fairly close to that given in reference 1, with the principal difference between the present results and those from reference 1 being associated with the less severe intensity of the turbulence noted previously.

Size of Turbulent Areas

The distribution of the horizontal extents or lengths of the turbulent areas, determined from the acceleration records, is given in figure 5 as the percent of the total number of areas within class intervals of 10 miles. The distribution is based on 115 turbulent areas encountered during the present operations between 20,000 and 55,000 feet. The distribution of turbulent areas given in reference 1 is also shown in the figure for comparison. For the present data, approximately 75 percent of the turbulent areas were less than 10 miles in length and less than 2 percent of the rough areas exceeded a length of 40 miles. Additional analysis of the data indicated that the distributions of the lengths of turbulent areas did not vary significantly with altitude for altitudes between 20,000 and 55,000 feet. Figure 5 shows that, on the average, the sizes of the turbulent areas for the present data appear to be somewhat smaller than those given by the results of reference 1. The smaller sizes for the present turbulent areas may also be associated with the limited seasonal coverage of the data of this investigation.

CONCLUDING REMARKS

An analysis of a small sample of turbulence data obtained from NACA VGH recorders during research flights of the Lockheed U-2 airplanes to attitudes of 55,000 feet over England and Western Europe during the summer of 1956 has indicated substantial reductions in the number and intensity of gusts with increasing altitude. The results indicated that the length of turbulent areas was less than 10 miles for about 75 percent of the areas encountered and that less than about 2 percent of the areas of rough air extended more than 40 miles. These results on the intensity, amount, and extent of atmospheric turbulence were found to be in overall agreement with the results given in NACA RM L53G15a for operations over the United States. The principal difference between the results of the two investigations was the indication that, on the whole, the turbulence encountered during the surveys over England and Western Europe was about 25 percent less severe than that for operations over the United States.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., December 17, 1956.

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2. Richardson, Norman R.: NACA VGH Recorder. NACA TN 2265, 1951.

3. Pratt, Kermit G., and Walker, Walter G.: A Revised Gust-Load Formula and a Re-Evaluation of V-G Data Taken on Civil Transport Airplanes From 1933 to 1950. NACA Rep. 1206, 1954. (Supersedes NACA TN's 2964 by Kermit G. Pratt and 3041 by Walter G. Walker.)

TABLE I.- FREQUENCY DISTRIBUTIONS OF DERIVED GUST VELOCITY BY ALTITUDE

Gust velocity, U_{de}, fps	Frequency distribution for altitudes, ft, of -			
	20,000 to 30,000	30,000 to 40,000	40,000 to 50,000	50,000 to 55,000
2 to 2.9	94	84	70	74
3 to 3.9	44	42	51	28
4 to 4.9	21	10	12	12
5 to 5.9	8	4	5	3
6 to 6.9	4	1	4	3
7 to 7.9	2	--	--	--
8 to 8.9	2	--	1	1
9 to 9.9	--	--	--	--
10 to 10.9	1	--	1	--
Total	176	141	144	121

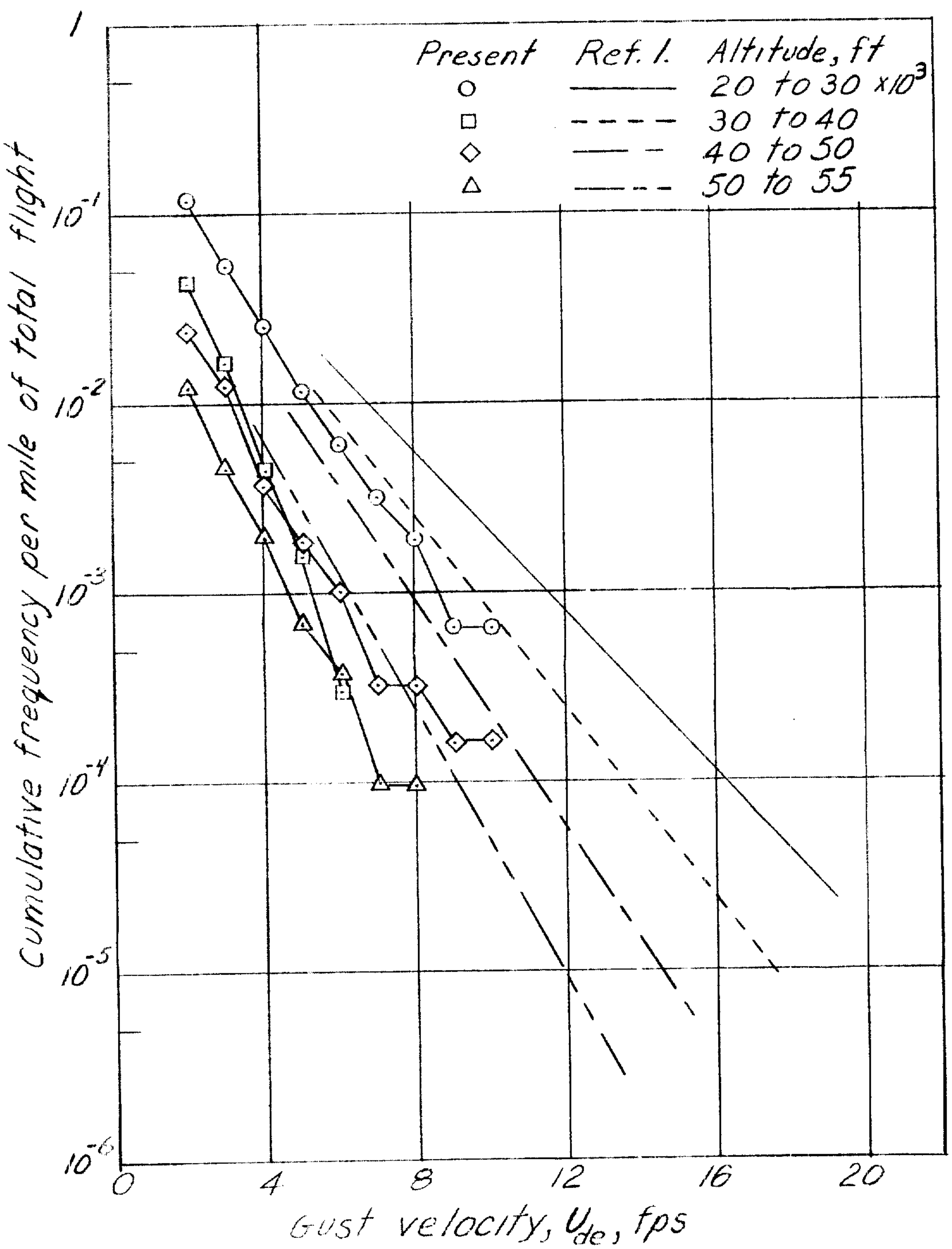

Figure 1.- Comparison of present results on the frequency of exceeding given values of gust velocity per mile of total flight with results from reference 1.

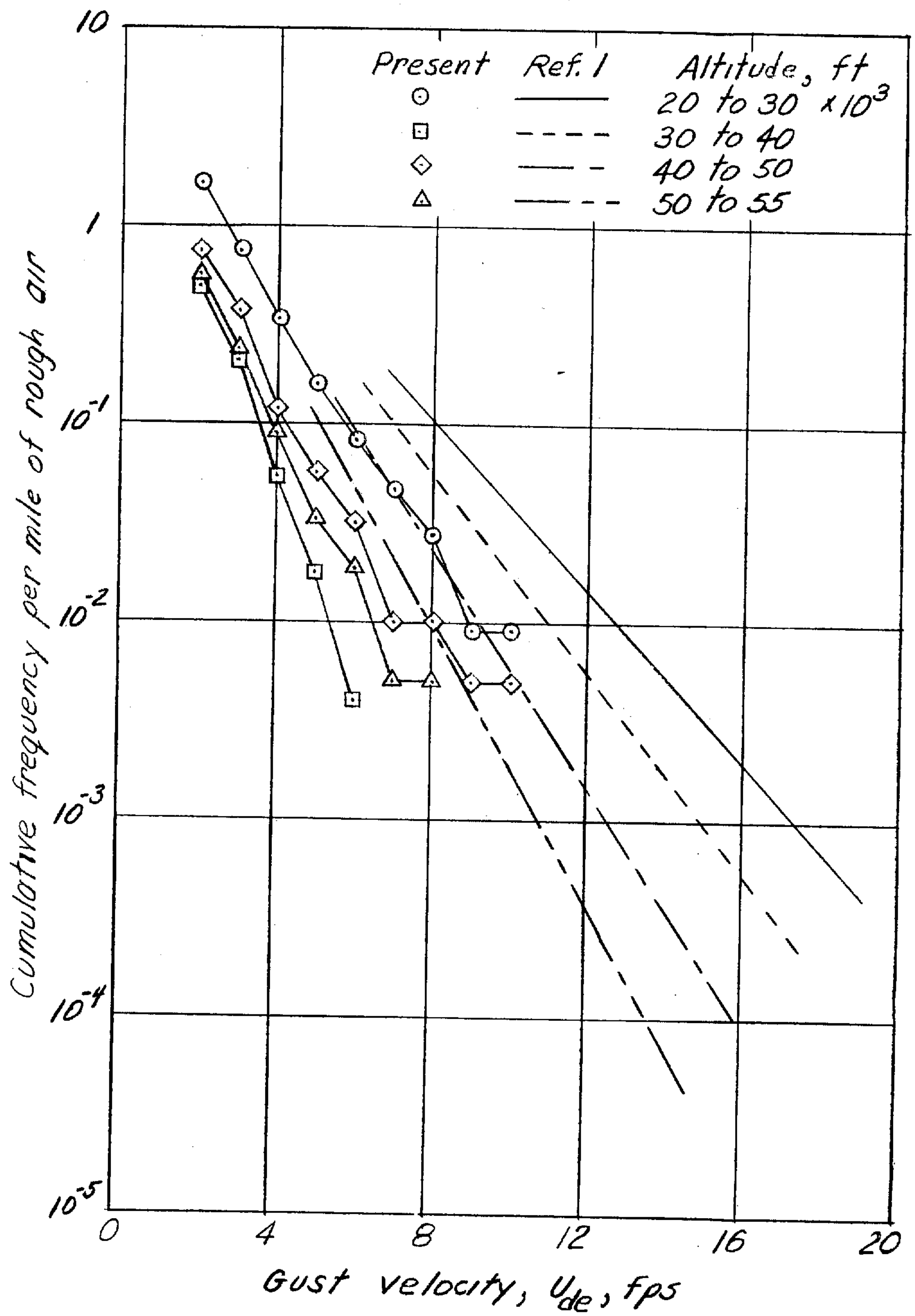

Figure 2.- Comparison of present results on the frequency of exceeding given values of gust velocity per mile of rough air with results from reference 1.

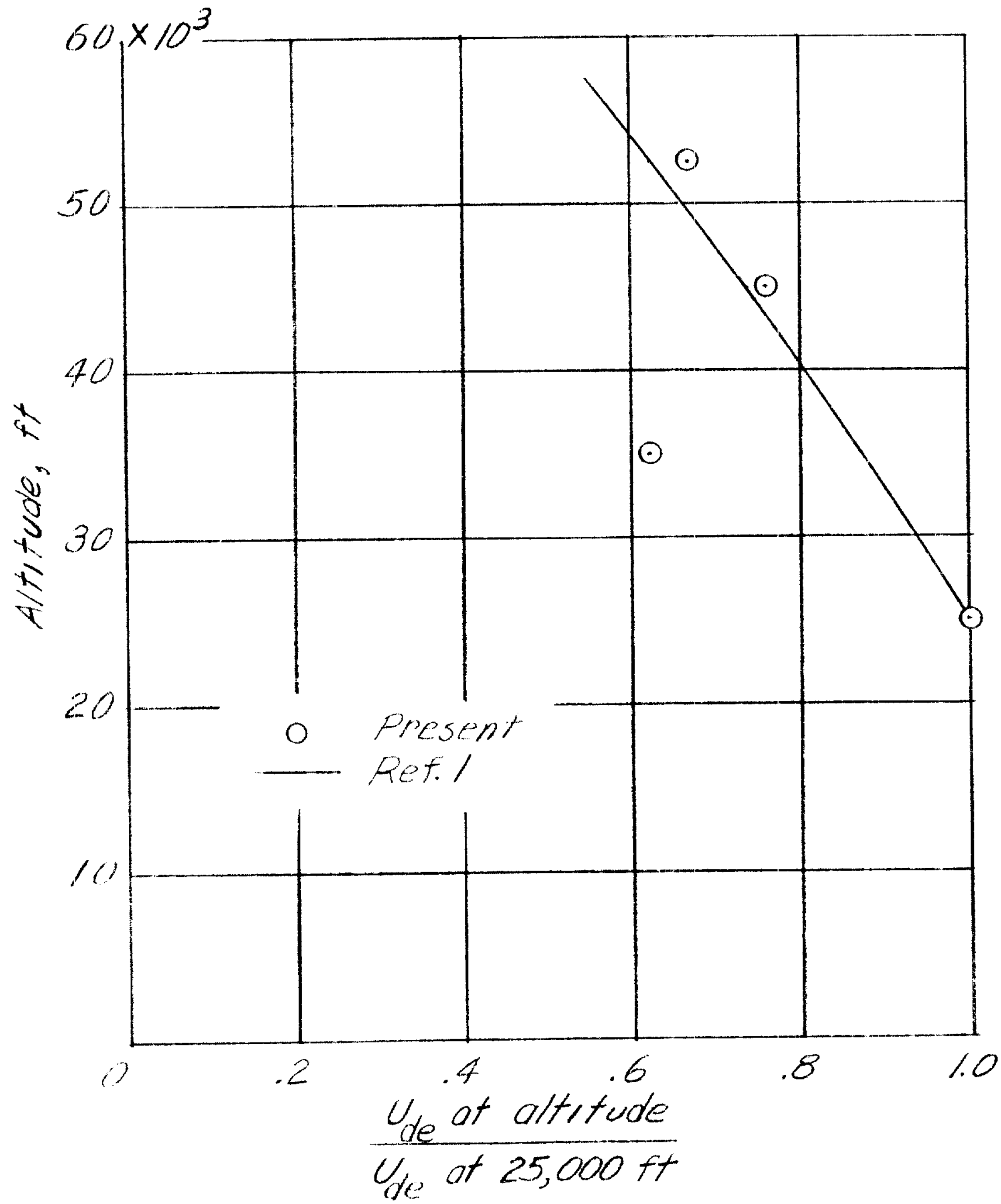

Figure 3.- Variation in relative gust velocities with altitude.

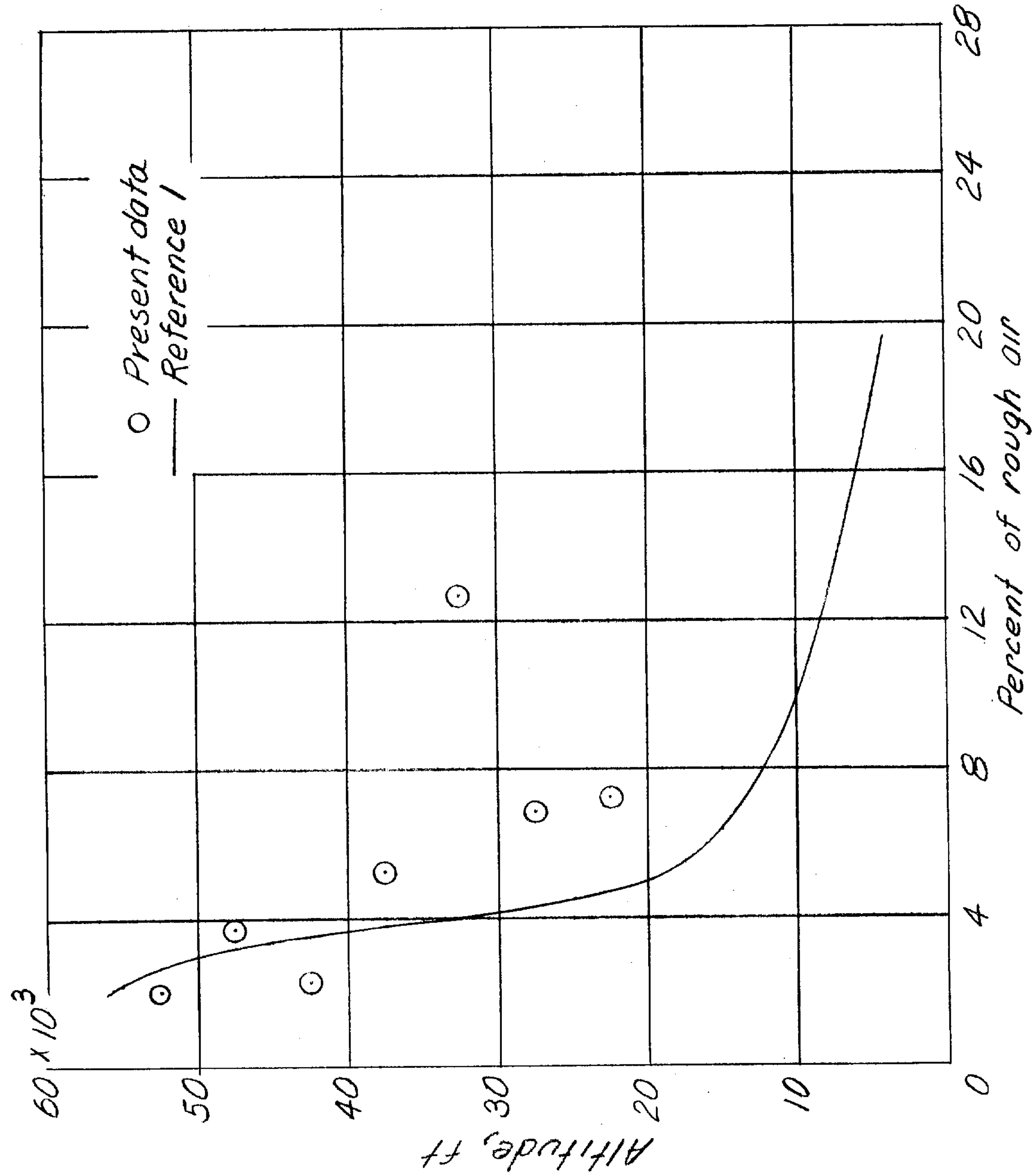

Figure 4.- Variation in percent of turbulent air with altitude.

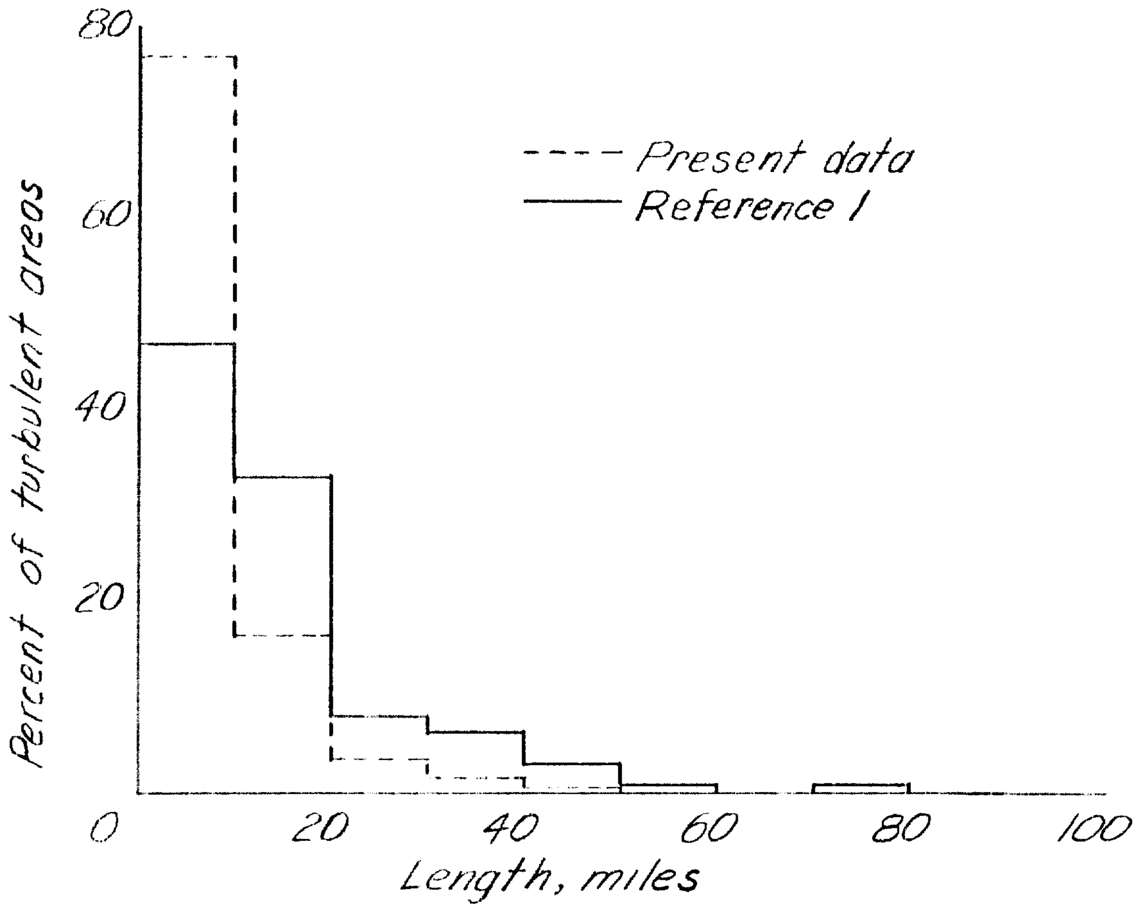

Figure 5.- Distribution of the lengths of turbulent areas for altitudes between 20,000 and 55,000 feet.

NACA RM L57A11
National Advisory Committee for Aeronautics.
PRELIMINARY MEASUREMENTS OF ATMOSPHERIC TURBULENCE AT HIGH ALTITUDE AS DETERMINED FROM ACCELERATION MEASUREMENTS ON LOCKHEED U-2 AIRPLANE. Thomas L. Coleman and Jack Funk. March 1957. 14p. diagrs., tab. (NACA RM L57A11)

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Copies obtainable from NACA, Washington

1. Loads, Gust - Wings (4.1.1.1.3)
2. Gusts, Atmospheric (6.1.2)
3. Operating Problems (7)

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III. NACA RM L57A11

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

1512 H Street, N.W. Washington 25, D.C.

FOR RELEASE MAY 7, 1957

These special instruments are carried by a Lockheed U-2 turbojet airplane in upper atmosphere research being conducted by the National Advisory Committee for Aeronautics. Research flights have been made at altitudes up to 55,000 feet over England and western Europe. First results of the continuing project have been published by NACA in Research Memorandum No. L57A11.

The instruments are:

1. Angular Velocity Recorder -- to record the airplane's rate of pitch;
2. Modified NACA VGH Recorder -- a highly sensitive device to measure and record head-on gust components in flight;
3. NACA VGH Recorder -- measures airplane acceleration, airspeed and altitude to provide record of magnitude and frequency of vertical gusts;
4. Flight Recorder Model BB -- keeps continuous record on arc-sensitized paper, of indicated airspeed, pressure altitude and normal acceleration;
5. Electrical Distribution Box;
6. Heading Amplifier -- amplifies signal input from gyrosyn compass and transmits to KS-4 Aerograph (No. 10);
7. Airspeed and Altitude Transducer -- measures pressure altitude and indicated airspeed and transmits to KS-4 Aerograph(No. 10);
8. NACA VGH Recorder -- scribes on smoked glass plate, acceleration and airspeed data;
9. VGH Acceleration Transmitter -- furnishes electrical input signals for VGH Recorder;
10. KS-4 Aerograph -- records pressure altitude, indicated airspeed, heading, indicated free air temperature, relative humidity, and true free air temperature;
11. Temperature and Humidity Measuring Set AN/AMQ-7 -- measures indicated free air temperature and indicated relative humidity and transmits to KS-4 Aerograph;
12. Vortex Thermometer System ML-470/AMQ-8 -- measures true free air temperature within one-half degree Centigrade at high speeds and transmits to KS-4 Aerograph.

LAL 57-1719

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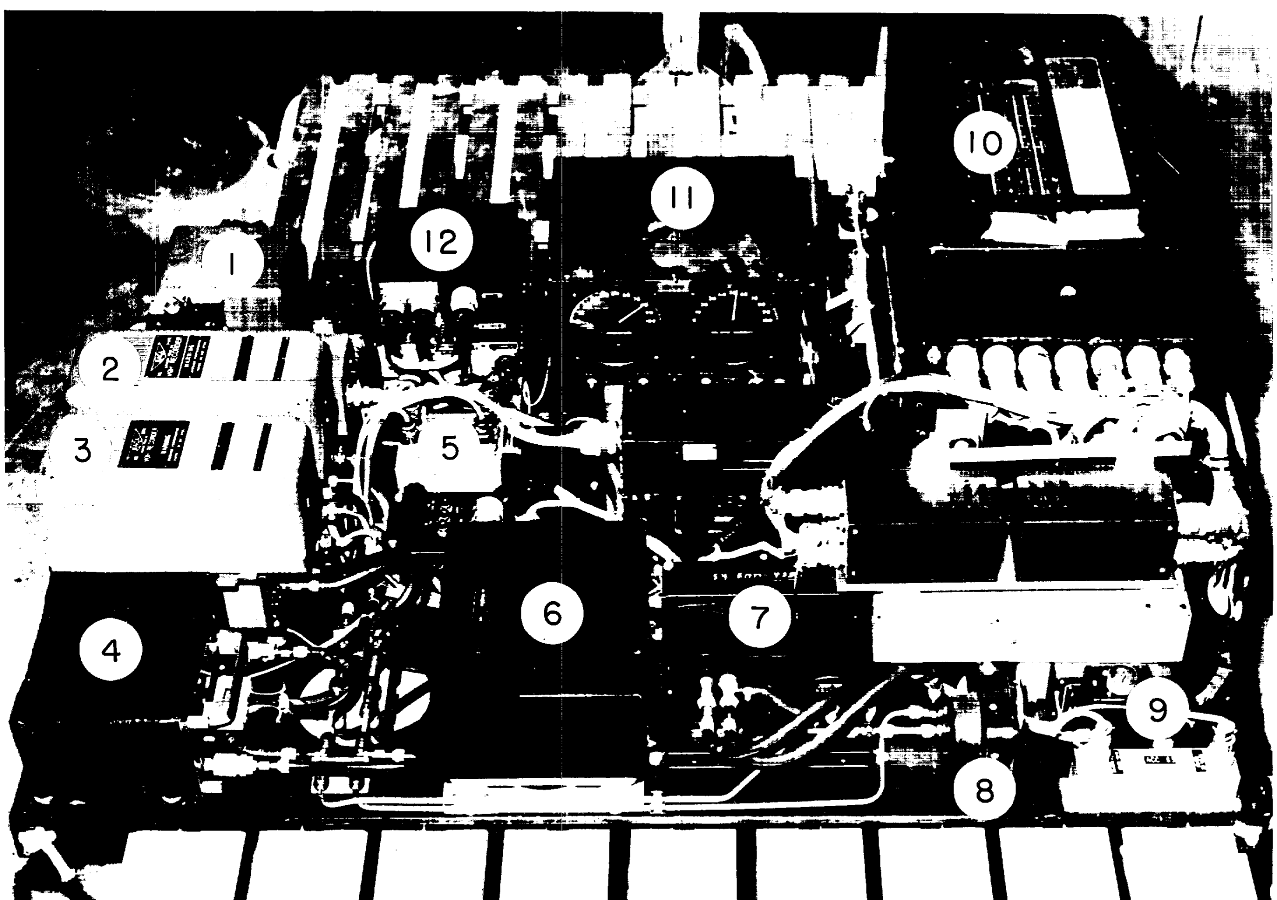
LAL 57-1719



NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

1512 H Street, N.W. Washington 25, D.C.

FOR RELEASE
MAY 7, 1957

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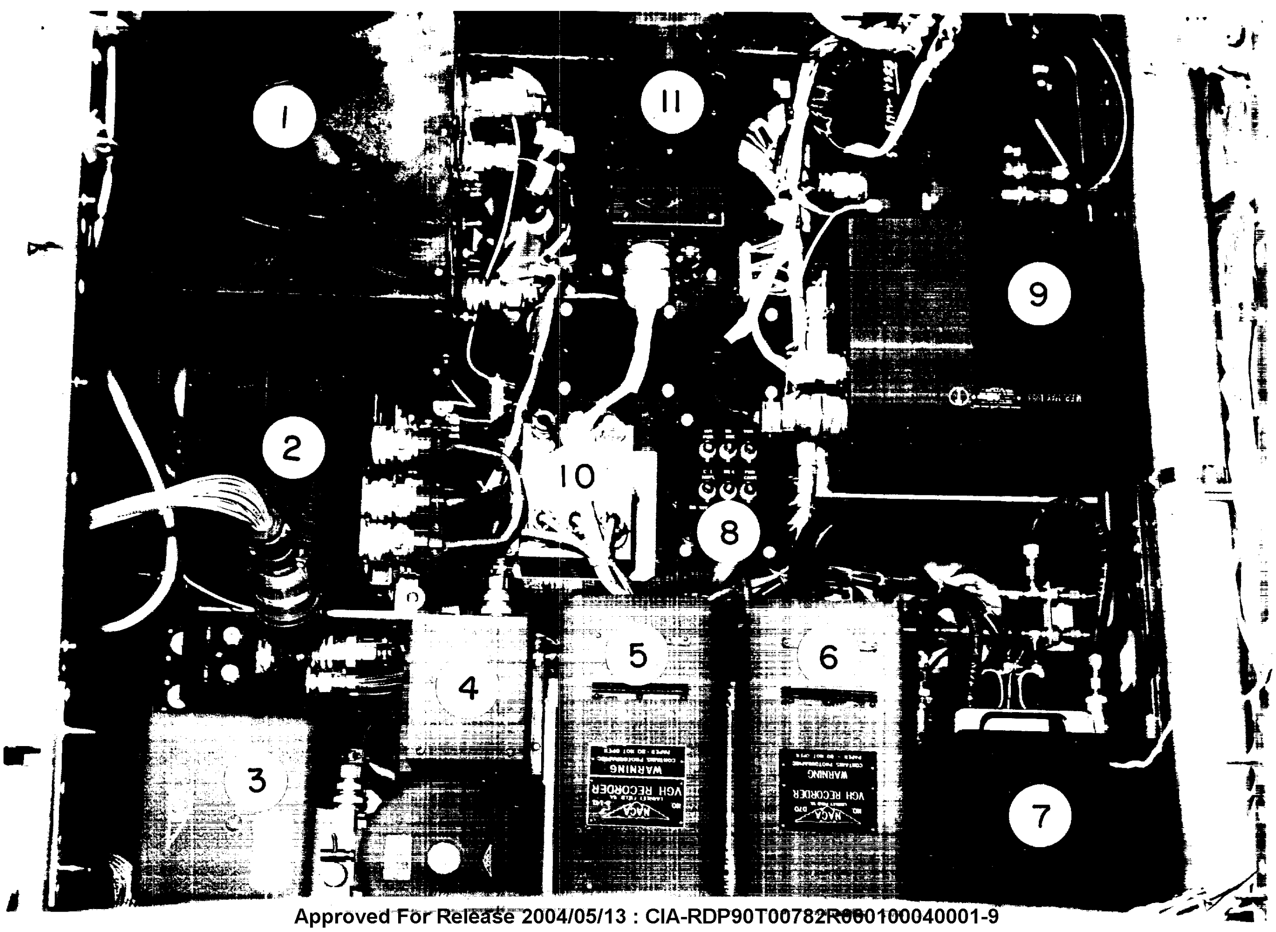
3. NACA Angular Velocity Recorder -- measures airplane's rate of pitch;
4. Timer -- synchronizes NACA recorders;
5. Modified NACA VGH Recorder -- highly sensitive, records head-on gust components in rough air;
6. NACA VGH Recorder -- provides magnitude and frequency of gusts by recording airplane acceleration, airspeed and altitude;
7. Flight Recorder Model BB -- records indicated airspeed, pressure altitude and normal acceleration;
8. Circuit-Breaker Panel;
9. Heading Amplifier -- amplifies signal from gyrosyn compass and transmits to KS-4 Aerograph system;
10. Electrical Distribution Box;
11. 400-Cycle Inverter -- operates from airplane power supply.

LAL 57-1720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NACA

RESEARCH MEMORANDUM

AIRPLANE MEASUREMENTS OF ATMOSPHERIC TURBULENCE FOR ALTITUDES BETWEEN 20,000 AND 55,000 FEET OVER THE WESTERN PART OF THE UNITED STATES

By Thomas L. Coleman and Emilie C. Coe

Langley Aeronautical Laboratory
Langley Field, Va.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

August 23, 1957

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

AIRPLANE MEASUREMENTS OF ATMOSPHERIC TURBULENCE FOR ALTITUDES BETWEEN 20,000 AND 55,000 FEET OVER THE WESTERN PART OF THE UNITED STATES

By Thomas L. Coleman and Emilie C. Coe

SUMMARY

A sample of data on atmospheric turbulence has been obtained from NACA VGH records taken on Lockheed U-2 airplanes during research flights covering approximately 40,000 miles for altitudes between 20,000 and 55,000 feet over the western part of the United States. An analysis of these data has indicated that the intensity, amount, and extent of atmospheric turbulence is in good agreement with earlier measurements obtained over England and Western Europe. In comparison with past estimates of average turbulence conditions over the United States, the results of this investigation, in general, indicate somewhat lower gust frequencies and lower gust intensities.

INTRODUCTION

During the early part of 1956, the National Advisory Committee for Aeronautics, 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 (ref. 1). The NACA participation in the program has been aimed primarily at obtaining information on the amount and intensity of atmospheric turbulence at high altitudes for use in airplane and missile response studies; whereas, the Air Weather Service has aimed at collecting data on humidity, pressure variations, and winds for associated operational and meteorological analysis.

The initial flight operations included in the program were undertaken concurrently over the western part of the United States and over England and Western Europe in the spring of 1956 and covered altitudes up to 55,000 feet. An analysis of the gust measurements obtained from the operations over England and Western Europe has been reported in reference 1. The results for the intensity and percent of rough air from the European operations were found to be in overall agreement with the estimates given in reference 2 for turbulence at high altitudes over the United States, although some differences in the intensity of turbulence for the two areas were indicated.

A sample of data on atmospheric turbulence covering approximately 40,000 flight miles for altitudes between 20,000 and 55,000 feet has been obtained from the operations over the western part of the United States. The present paper presents the results obtained for the frequency and intensity of the turbulence encountered in these operations and compares these results with those given in references 1 and 2.

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 the test airplane is shown in figure 1.

The measurements pertinent to this report consisted of time-history records of airspeed, acceleration, and pressure altitude taken with NACA VGH recorders (ref. 3). The time histories were recorded on photographic paper moving at 4 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 above 50,000 feet. In general, the flight plans consisted of climbing to an altitude of approximately 50,000 feet in the vicinity of the operations base (Watertown Strip, Nevada), cruising initially at about 50,000 feet with the altitude gradually increasing to about 55,000 feet as the fuel load decreased, and then descending to the operations base. As a consequence of this flight procedure, the gust measurements below 50,000 feet were obtained only during the climb and descent phases of the flight and the measurements above 50,000 feet were taken primarily during cruising flight. The data below 50,000 feet essentially represent soundings of the atmosphere and thus reflect the turbulence conditions which exist in the general region of Watertown Strip, Nevada. The cruise portions of the flights between 50,000 and 55,000 feet, in general, covered the Rocky Mountain and the Pacific Coast regions of the United States.

Records were obtained from 24 flights during operations from Watertown Strip, Nevada, between May 1956 and March 1957 with about one-half of these flights being made during the three-month winter season from December 1956 to February 1957. The flight schedules were based primarily on airplane and instrumentation availability, and no attempt was made to schedule flights to sample turbulence for specific meteorological conditions. Except for occasional penetrations of stable cloud formations while climbing or descending, the flight miles flown during the present operations were in clear air. The data above 50,000 feet, therefore, are felt to be fairly representative of clear-air turbulence conditions over the western part of the United States.

The scope of the data in terms of miles flown within different altitude intervals is listed at the bottom of table I. As shown in the table, about 37,000 flight miles or approximately 90 percent of the total flight miles were flown between 40,000 feet and 55,000 feet, and only a relatively small number of flight miles were in each of the two lower altitude intervals.

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 and 2 and are given briefly in the following paragraphs.

The vertical gust velocities were derived from simultaneous readings of acceleration, airspeed, and altitude through the use of the gust equation which is given in reference 4 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 complete frequency counts of all gust velocities greater than 2 feet per second. Values of airspeed and pressure altitude were obtained from the records for each acceleration 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 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 gust-velocity values presented herein may be open to some question because of 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, 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, such as references 1 and 2. The length of each turbulent area was found simply 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 percent of rough air for that altitude interval.

RESULTS AND DISCUSSION

Overall Gust Distributions

The gust velocities derived from the acceleration and airspeed data are presented as frequency distributions in table I for several altitude intervals between 20,000 and 55,000 feet. Inspection of the table shows that the maximum gust velocities encountered in the present operations were approximately 12 feet per second and were experienced in altitude intervals from 20,000 to 30,000 feet and from 50,000 to 55,000 feet. Only 19 gusts above 2 feet per second were encountered in approximately 7,000 miles of flight in the altitude interval between 40,000 and 50,000 feet and, consequently, the distribution of gust velocities for this altitude interval is not well defined. As noted previously, the data below 50,000 feet were obtained during the climb and descent portion of the flights and may be biased by turbulent conditions peculiar to the general region of Watertown Strip, Nevada.

The gust-velocity data from table I are shown in figure 2 as cumulative frequency distributions per mile of flight for each altitude interval. These cumulative frequency distributions give the average number of gusts per mile of flight which exceeded given values of gust velocity. Examination of figure 2 shows that large variations exist in the frequency with which given gust velocities were encountered in the various altitude intervals and that, in general, the gust frequency decreased with increasing altitude.

Figure 3 compares the present results for the gust frequency at the different altitudes with the results for corresponding altitudes from references 1 and 2. The results from reference 2 are based on the basic distribution of nonthunderstorm turbulence and the variation of gust intensity with altitude. It should be noted that the present results and those from reference 1 are for specific geographical regions, whereas the results from reference 2 are estimates of average turbulence conditions over the United States.

Inspection of figure 3 shows that the present results are in good agreement with the results from reference 1 for operations over Western Europe, except for the altitude interval of 40,000 to 50,000 feet. Both sets of data from the present investigation and reference 1 indicate lower gust frequencies for each altitude interval than those given by the estimates based on reference 2. Thus, it appears that estimates of gust frequencies for clear-air turbulence based on reference 2 may be somewhat high in comparison with operations over the western part of the United States and Western Europe.

Intensity of Turbulence

The overall gust distributions discussed in the preceding section may be considered to reflect the combined effects of the intensity of the turbulence and the percent of rough air at the various altitudes. In order to examine the turbulence encountered in more detail, it is helpful to consider separately the gust intensity and the percent of rough air. As a measure of the severity of the turbulence, the cumulative frequency distributions of gust velocity per mile of flight in rough air are plotted in figure 4 for the various altitude intervals. Inspection of figure 4 shows that differences on the order of 20 to 1 exist between the frequency of occurrence of given gust velocities per mile of flight in rough air at the various altitudes. Although the results indicate a lower gust intensity for the highest altitude interval

(50,000 to 55,000 feet) than for the lowest altitude interval (20,000 to 30,000 feet), these results do not exhibit the continuous decrease in gust intensity with increasing altitude shown by previous results (ref. 2).

In order to compare the present results for the intensity of turbulence with previous results, the cumulative frequency distributions of gust velocities per mile of flight in rough air within different altitude intervals are shown in figure 5 together with corresponding results from references 1 and 2. These results indicate that, in general, the intensity of the rough air encountered in this investigation is approximately the same as that reported in reference 1 for operations over Western Europe but is lower than that estimated in reference 2 for average operations over the United States. For the altitude interval of 30,000 to 40,000 feet, in particular, the intensity of the turbulence encountered in both the present investigation and in reference 1 appears to be much lower than is shown by the estimates from reference 2.

Percent of Rough Air

The percent of the flight distance which was in rough air is presented in figure 6 for each 5,000-foot altitude interval. For comparison, similar results from references 1 and 2 (the latter results based on airplane and telemeter data) are also given in the figure. Figure 6 indicates that the percent of rough air from both the present flights and European flights (ref. 1) is in fair agreement with the results of reference 2 at the lowest and highest altitudes, but that the data from the present report and from reference 1 indicate a much higher percent of rough air between 30,000 and 40,000 feet.

It may be noted that the percent of rough air (ref. 2) is based on a fairing of some of the earliest available data on the variation of the percent of rough air with altitude. Although some of these early data indicated a peak in the percent of rough air at altitudes of 30,000 to 40,000 feet, this indication was given little weight in the fairing because of the limited data available at that time. The consistency of the two sets of results from the present report and from reference 1 and reconsideration of the earlier data used in reference 2, however, suggest that a peak does exist between 30,000 and 40,000 feet in the variation of the percent of rough air with altitude. As noted previously, however, the intensity of the turbulence for this altitude interval is relatively low. This increase in the percent of rough air is probably associated with high winds and wind shears which are prevalent at 30,000 to 40,000 feet for the regions covered by the data (refs. 5 and 6).

Size of Turbulent Areas

The distribution of the lengths of the turbulent areas is given in figure 7 as the percent of the total number of areas which was within class intervals of 10 miles. For comparison, the distributions of turbulent areas given in references 1 and 2 are also shown in the figure. Inspection of the results in figure 7 shows that the distribution of turbulent areas from this investigation is in good agreement with the results from references 1 and 2 and that the majority of the turbulent areas were less than 20 miles in length. A breakdown of the present data showed no significant variations between the distributions of the lengths of turbulent areas for altitudes of 20,000 to 50,000 feet and for 50,000 to 55,000 feet. This result is in agreement with the results of references 1 and 2.

CONCLUDING REMARKS

The results of an analysis of a sample of data on atmospheric turbulence obtained from NACA VGH recorders during research flights of Lockheed U-2 airplanes to altitudes of 55,000 feet over the western part of the United States between May 1956 and March 1957 substantiate earlier indications of a decrease in the frequency of occurrence of gusts with increasing altitude. The intensity of the turbulence, the percent of rough air, and the length of the turbulence areas generally were found to be in good agreement with the results given in NACA Research Memorandum L57A11 for operations over England and Western Europe. In comparison with the earlier estimates given in NACA Research Memorandum L53G15a for operations over the United States, however, the present results generally show a lower gust frequency and lower gust intensities. In addition, the present results and those of NACA Research Memorandum L57A11 indicate a higher percent of rough air between 30,000 and 40,000 feet than is given by the estimates in NACA Research Memorandum L53G15a. These results, together with a reconsideration of earlier data, suggest that a peak exists in this altitude range in the percent of rough air with altitude. However the intensity of the turbulence in this altitude range appears to be light.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., June 17, 1957.

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5. Tolefson, H. B.: An Investigation of Vertical-Wind-Shear Intensities From Balloon Soundings for Application to Airplane- and Missile-Response Problems. NACA TN 3732, 1956.

6. Widger, William K., Jr.: A Survey of Available Information on the Wind Fields Between the Surface and the Lower Stratosphere. Air Force Surveys in Geophysics No. 25, Air Force Cambridge Res. Center, Dec. 1952.

TABLE I.- FREQUENCY DISTRIBUTIONS OF DERIVED GUST VELOCITY

FOR VARIOUS ALTITUDE INTERVALS

Gust velocity, U_{de}, fps	Frequency distribution of gust velocity for altitudes of -			
	20,000 to 30,000 ft	30,000 to 40,000 ft	40,000 to 50,000 ft	50,000 to 55,000 ft
2 to 3	142	83	18	120
3 to 4	41	13	1	57
4 to 5	16	4		28
5 to 6	8	1		10
6 to 7	6	1		9
7 to 8	1			3
8 to 9	1			1
9 to 10	0			1
10 to 11	1			0
11 to 12	0			1
12 to 13	1			
Total	217	102	19	230
Miles of flight in rough air	114	216	57	366
Total flight miles	1,203	1,430	6,962	30,244

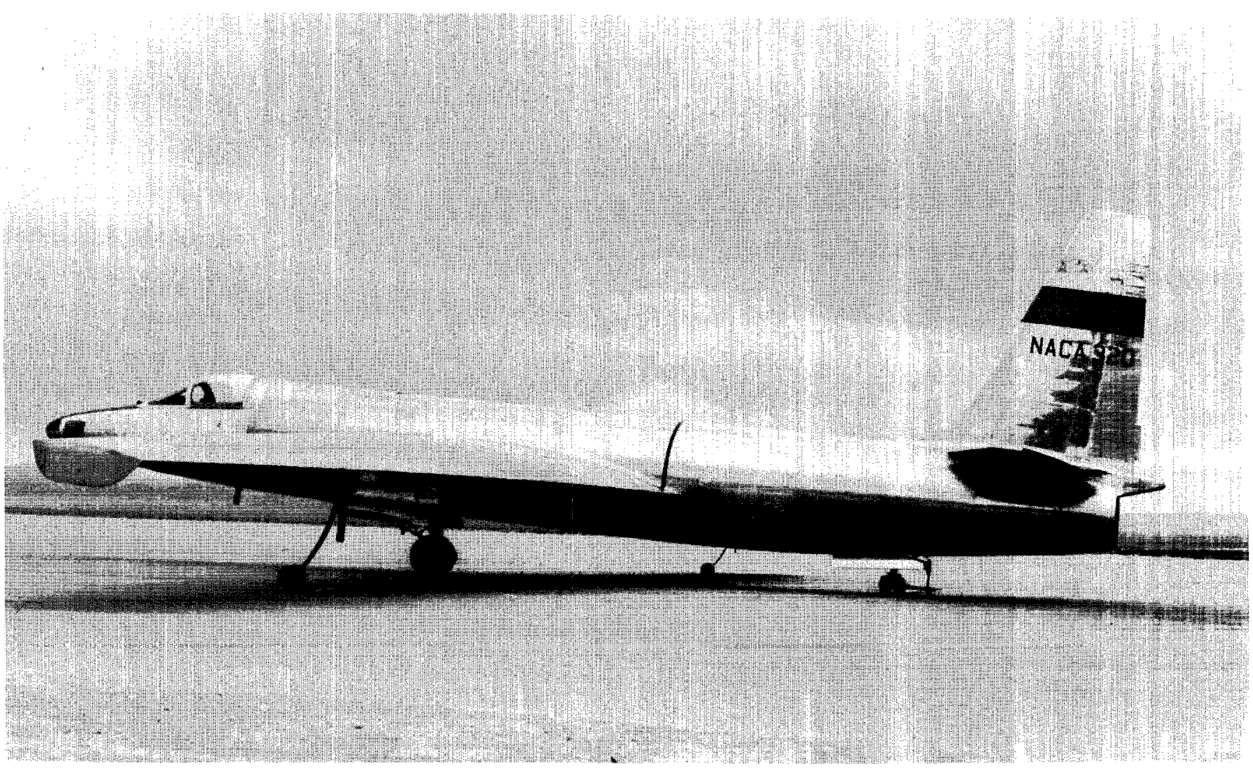


Figure 1.- Photograph of test airplane. L-57-96

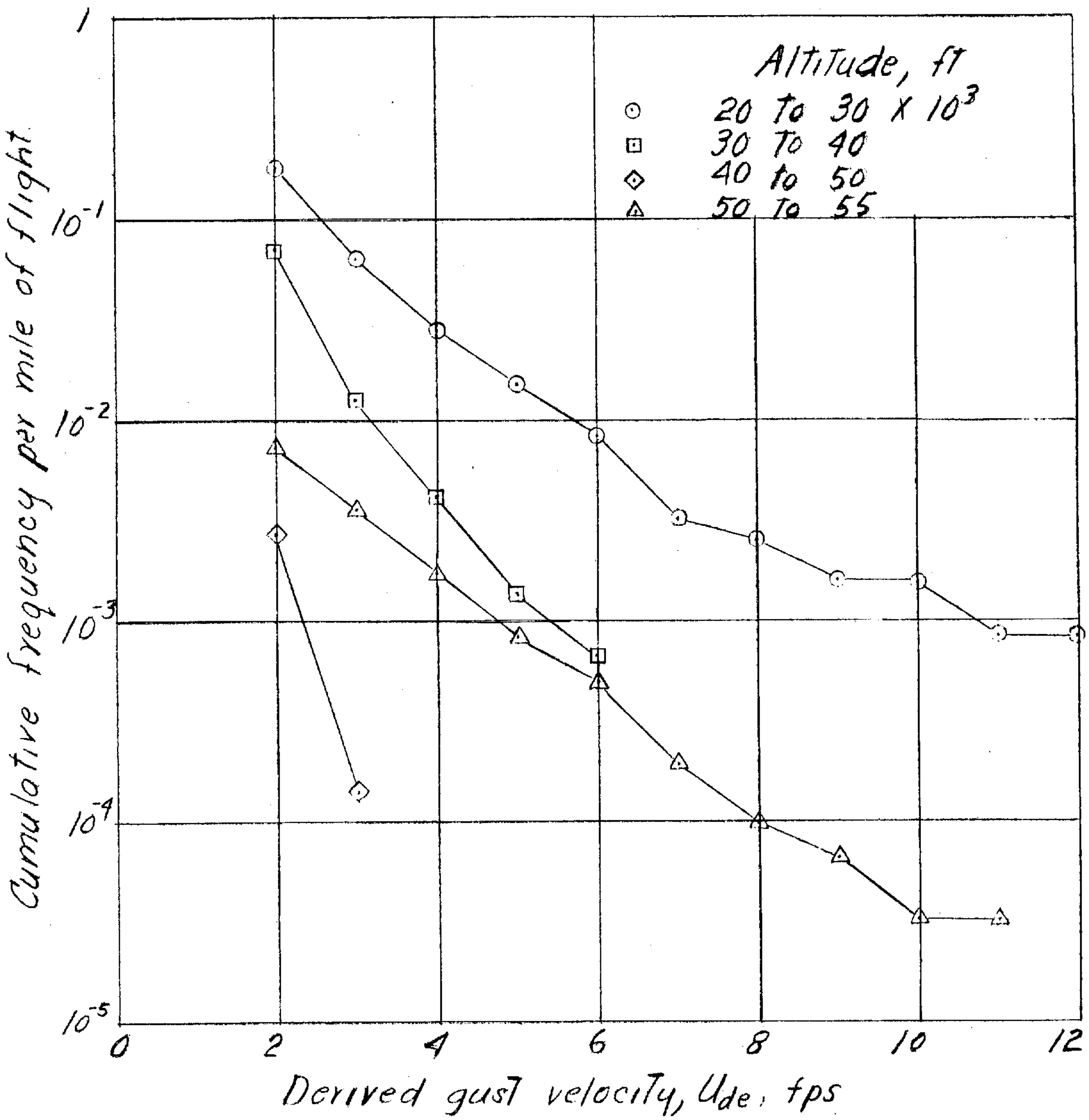
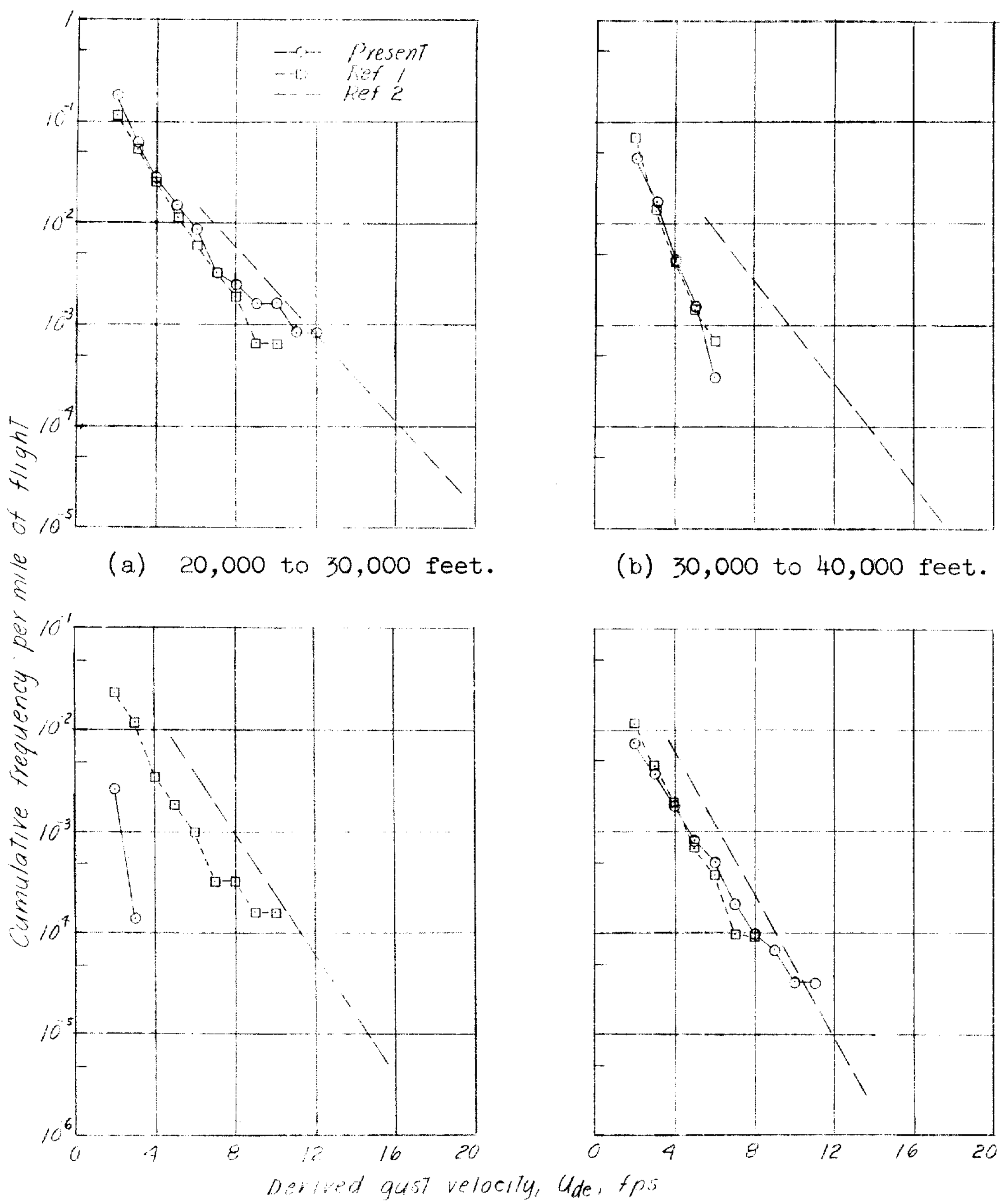


Figure 2.- Variation with altitude of the frequency of exceeding given values of gust velocity per mile of total flight.



(a) 20,000 to 30,000 feet.

(b) 30,000 to 40,000 feet.

(c) 40,000 to 50,000 feet.

(d) 50,000 to 55,000 feet.

Figure 3.- Comparison at various altitudes of present results for the frequency of exceeding given values of gust velocity per mile of flight with results from references 1 and 2.

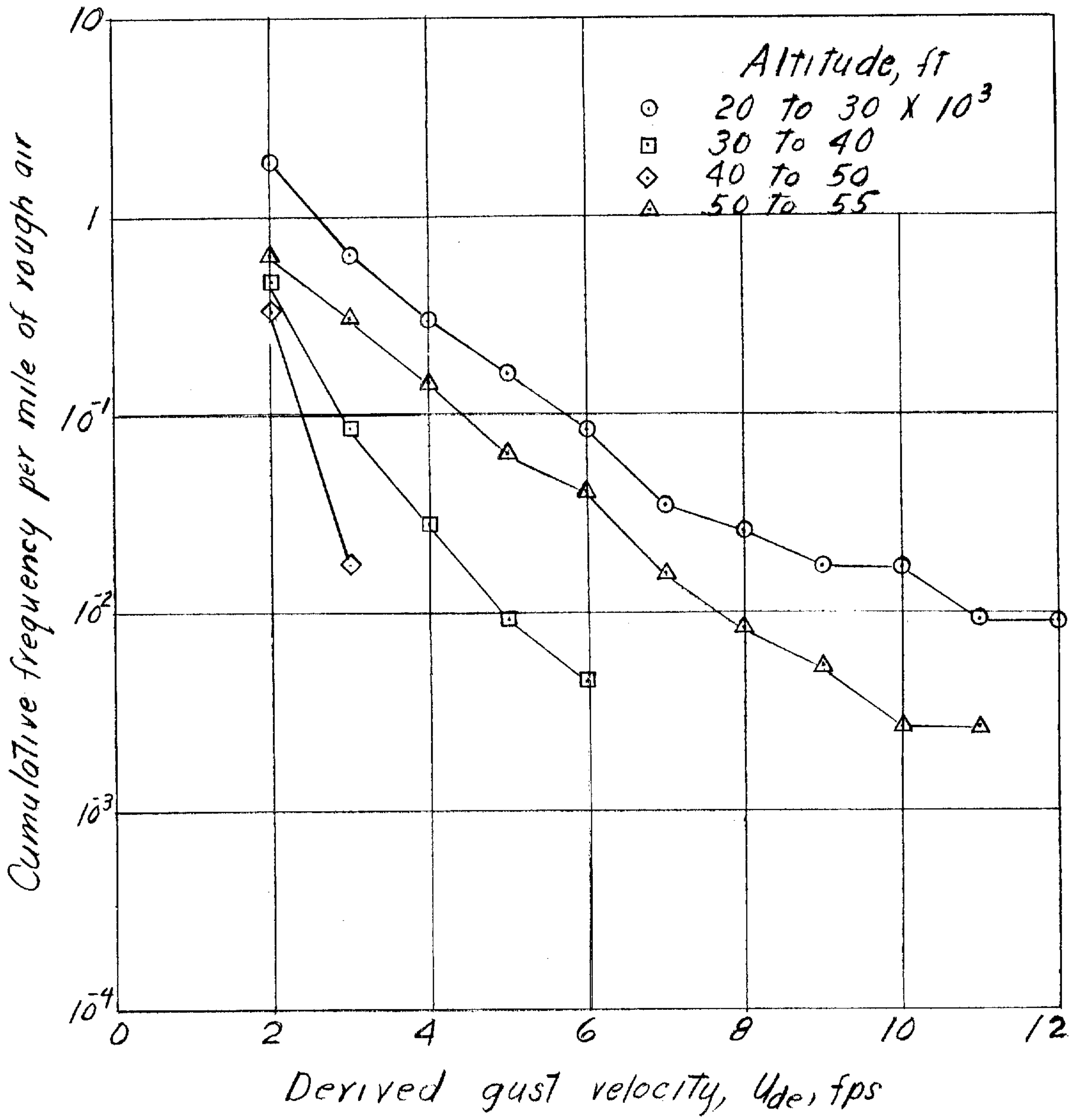
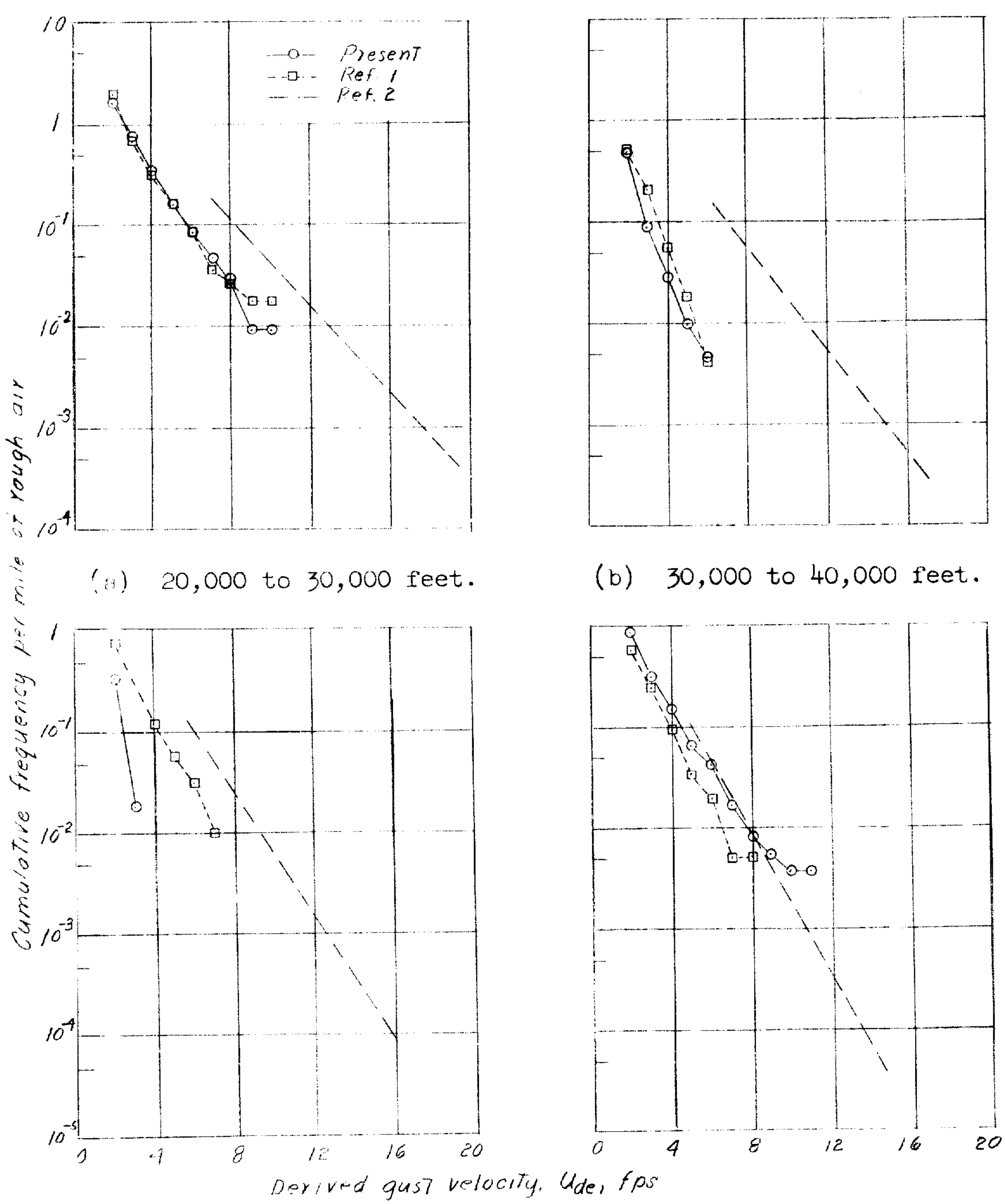


Figure 4.- Variation with altitude of the frequency of exceeding given values of gust velocity per mile of rough air.



(a) 20,000 to 30,000 feet.

(b) 30,000 to 40,000 feet.

(c) 40,000 to 50,000 feet.

(d) 50,000 to 55,000 feet.

Figure 5.- Comparison at various altitudes of present results on the frequency of exceeding given values of gust velocity per mile of rough air with results from references 1 and 2.

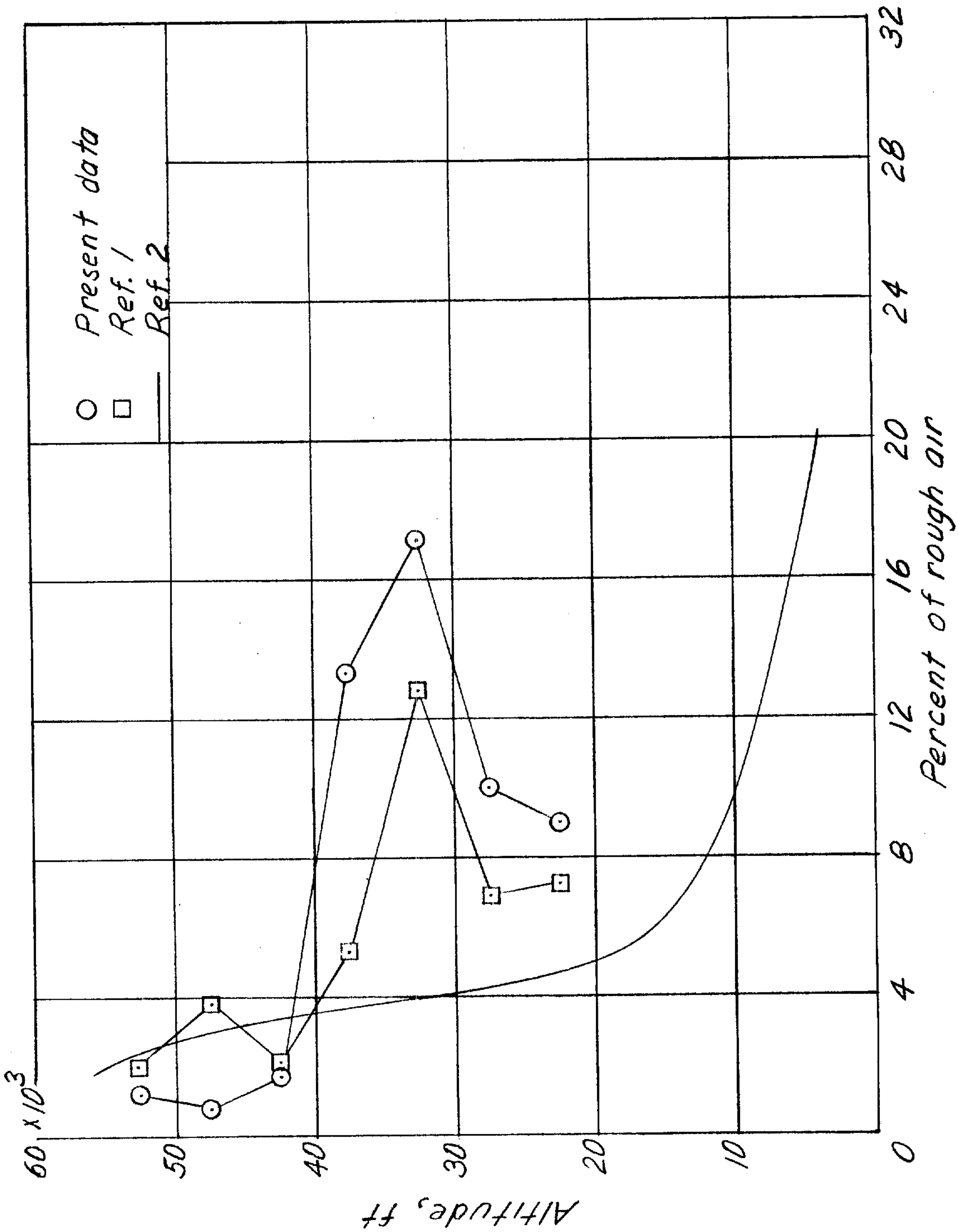


Figure 6.- Variation in percent of clear-air turbulence with altitude.

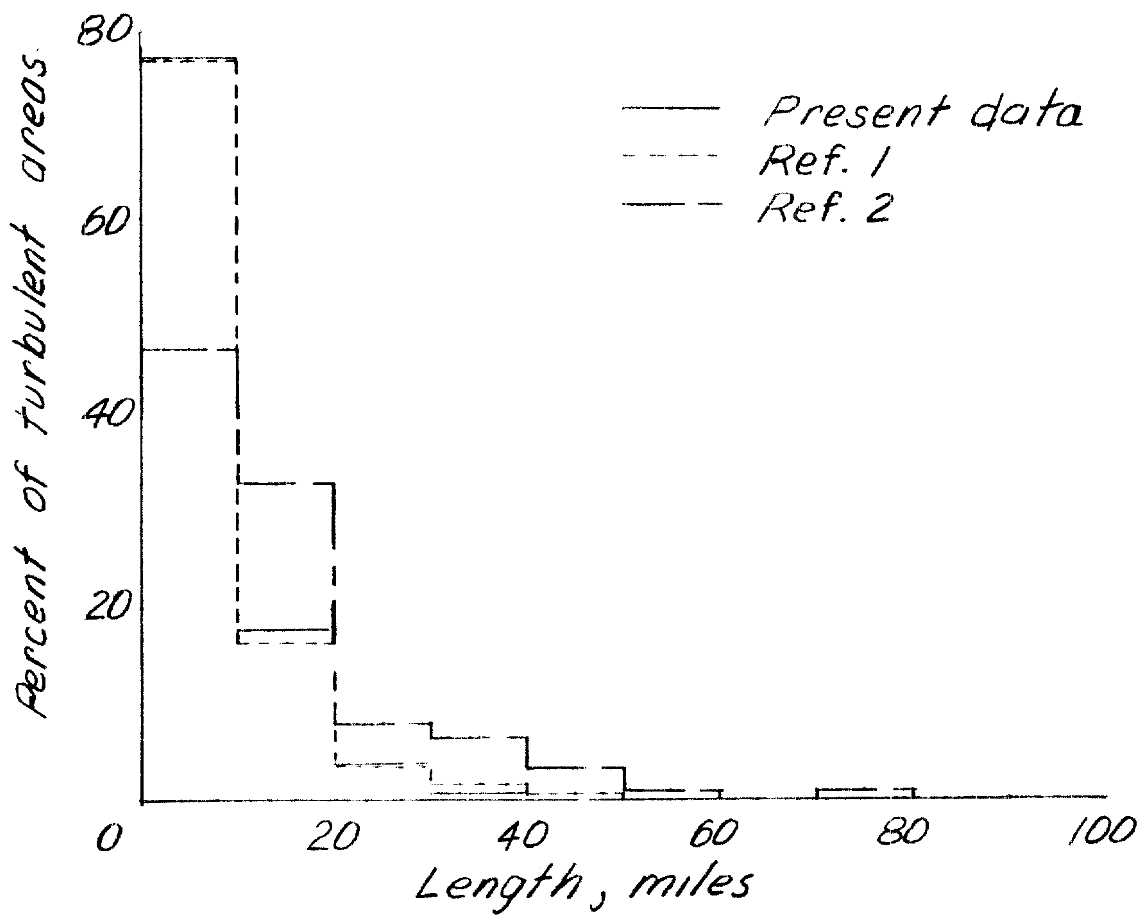


Figure 7.- Distribution of the lengths of turbulent areas for altitudes between 20,000 and 55,000 feet.

NACA RM L57G02
National Advisory Committee for Aeronautics.
AIRPLANE MEASUREMENTS OF ATMOSPHERIC TURBULENCE FOR ALTITUDES BETWEEN 20,000 AND 55,000 FEET OVER THE WESTERN PART OF THE UNITED STATES. Thomas L. Coleman and Emilie C. Coe. August.1957. 16p. diagrs., photo., tab. (NACA RM L57G02)

An analysis of a sample of data on atmospheric turbulence obtained from NACA VGH records taken on Lockheed U-2 airplanes during research flights covering approximately 40,000 miles for altitudes between 20,000 and 55,000 feet over the western part of the United States is presented. The results for the variation of intensity and amount of turbulence with altitude are compared with turbulence data previously obtained from similar operations over England and Western Europe and with earlier estimates of average turbulence conditions over the United States.

Copies obtainable from NACA, Washington

1. Loads, Gust - Wings (4.1.1.1.3)
2. Gusts, Atmospheric (6.1.2)
3. Operating Problems (7)
I. Coleman, Thomas L.
II. Coe, Emilie C.
III. NACA RM L57G02

NACA

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Air Weather Service
APO 925, USAF
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1993 words

THE FIRST FLYOVER OF A TROPICAL CYCLONE

By Lt. Col. Robert C. Bundgaard

For the flying weathermen of the Weather Reconnaissance Squadron, Provisional (3rd), the mission was a new one, never previously tried. It was their task to conduct a reconnaissance of Typhoon Kit from above using the Perkin-Elmer Model-501 tracking camera. This horizon-to-horizon aerial camera would wipe Kit's image onto 70mm film with a continuously-rotating scanning-prism. The Model-501 is small and light enough to be carried aloft by WRSP/3's U-2 jet aircraft, operated by the Air Weather Service in support of the National Advisory Committee for Aeronautics' upper air research program.

To Americans back home, last year's Typhoon Kit in the Pacific is probably not cloaked with as much ill-repute as was her eldest sister Agnes, that earlier brought havoc and destruction to our military installations in Okinawa. But Kit is well remembered in the Republic of Philippines. Coinciding with the recent presidential election, Kit behaved very much unlike our Lady of Liberty and suspended for upwards of a million citizens of the Republic the exercise of their constitutional right to vote.

Surveyed in her aftermath, Kit wrought over five million dollars damage to public works, private property, the maturing rice and palay crops. She rendered some 58,900 known persons homeless, probably many more. Despite her vicousness, miraculously she claimed the lives of only 39 persons, but including United States Marine Private First Class Charles Leon Davis, with a provisional camp of "Operation Strong Back," drowned in the valley-widened Coronel River. Yet, for all her waste, suffering and lives lost, Typhoon Kit could well have led to a far greater catastrophe, were it not for the typhoon warnings promptly and amply provided days in advance by Lt. Col. Howard Berg's 54th Weather Reconnaissance Squadron, based at Guam's Andersen Air Base, and utilizing the proven WB-50 aircraft.

Meandering westward over the Eastern Carolines Islands during the early days of last November, the South Pacific tradewinds, it might be presumed, momentarily wobbled and recurved northward, spanking rotation and life into a small depression there. The mothering trades then nursed this feebly turning depression with her moisture-enriched hot breath. Doddering westward attached to the trades' apron strings, the progressively strengthening and growing whirl gained in storm intensity. On the morning of November 8th, Colonel Berg's vigilant typhoon chasers first spotted this new, trade-spawned storm practically in their own backyard, just 170 miles south-southwest of Guam. When first found, it was already spewing 50-mile-per-hour winds. By that same afternoon, the storm had intensified into a full blown typhoon, to be dubbed Kit. The watching of Kit by the 54th began.

Typhoon Kit plowed west-northwest at 20 miles per hour toward the Philippines, 930 miles away. Riding herd on Kit during the next three days of fatiguing and teeth chattering flights, the 54th weather crews twelve times boxed the typhoon and penetrated into its very eye. Flirting with death in Kit to give precious warning for the safety of the Philippines, little did these flying weathermen suspect that fate had destined among them a crew to be lost soon in these very same waters, now lashed and churned below them by Kit in all her devilish fury; just two months later a WB-50 from the 54th disappeared into Typhoon Ophelia, following Kit's same path, and was never heard from again.

On November 11th, the eve of the Philippines national elections, Kit packed 200 mile-per-hour surface winds, only a day out of Luzon. Despite the fury of these howling winds, the 54th continued to look three times more into Kit's bewitching eye, as she skirted north past Catanduanes Island, passed within 60 miles to the north of the Bicol Peninsula, and until at last she poised to stab into East Central Luzon at Baler Bay.

As Kit travelled inland, the rugged mountainous terrain of Luzon took a lot of wind out of her, at least in the lower part of the typhoon. Steered under the influence of the upper southerlies, Kit now curved abruptley northward into a parabolic swing, barely sideswiping Clark

Air Base. Apparently with the prophetic power that would be the envy of even the greatest of soothsayers, USAF typhoon forecasters had gathered at Clark Air Base from throughout the Far East and were midway through a two-week Typhoon Workshop, being carried out under the auspices of Professor C. S. Ramage and Major James Sedler from the University of Hawaii. The workshoppers followed Kit closely, predicting her movement by various techniques. Only one technique successfully called for Kit's sudden swing northward through Luzon after its four-day trek westward. This technique is an empirical method recently developed by Keith Veigas and Robert Miller at Traveler's Weather Research Center, Hartford, Conn., under the leadership of Dr. Thomas Malone.

Noon the next day, after exhausting her strength in battering the Luzon land cap, Kit bid her pallam, or adieu, and slipped out of the Ilocos coast, at a point 30 miles east of the coastal city of Aparri, at the Cagayan delta. Now subdued, erratic Kit turned back to the Pacific, zigzagging sluggishly northward and skirting east of the Batanes Islands.

But now, as Typhoon Kit threatened to recurve to the northeast in the direction of Okinawa, the responsibility for watching her passed to the 56th Weather Reconnaissance Squadron and the 3rd Weather Reconnaissance Squadron, Provisional, both units based in Japan. Again the WB-50 was dispatched to keep a watchful eye on Kit. The suspense of such flights was now beginning to appear among the personnel of WRSP/3.

By noon on the 14th of November, Typhoon Kit had reached a critically interesting degenerative stage. Few opportunities had thus far been afforded to scientists for studying the manner in which typhoons dissipate into tropical storms, thence into tropical depressions or sometimes into fast moving sub-tropical cyclones. Sometimes, typhoons temporarily weaken into separate storms, such as Kit did, only to be reborn again as typhoons. Scientists had long hoped for the opportunity to examine a typhoon from above with the hope that it might shed some light upon which of these dissipating atmospheric processes man, in the future, might himself most easily seek to alter in order to control typhoons.

So, as Kit mauled indecisively at 20°N and 123°E, Dr. Robert D. Fletcher, past president of the American Meteorological Society, visiting with the WRSP/3, suggested that now was the time for WRSP/3 to dispatch one of its U-2 research aircraft to seek Kit out. Approaching the storm area the WRSP/3 pilot was guided by giant cloud "streets" spiraling in toward a coliseum-like wall of nimbostratus which surrounded Kit's eye. In the wide converging sectors between these towering squall bands, a floor of soft flat clouds hid the ocean from the pilot's view. Climbing into the storm center, the U-2 hedge-hopped over the towering 48,000 foot cloud wall which surrounded the eye of Kit. Once within this wall, 10 miles above the ocean's surface, the pilot saw the angried ocean and far below him the waves were clearly visible through the long arcing moats, clear of cloud. Downdrafts of hot air had gouged out these moats at the eye-wall's very edge. Looking much like the froth on a boiling caldron, a large moat-ringed island of low and hard cauliflowery clouds bleared Kit's eye. Around an island centered hub-cloud, the eye cloud churned [illegible] pilot counted nine such cat eyes within the center of Kit. These false-eyes were parasitically consuming the dying typhoon, much in the manner so aptly described by L. F. Richardson in his famous book Numerical Weather Prediction (1922, p. 66):

Big whirls have little whirls that feed on their velocity,
And little whirls have lesser whirls and so on to viscosity.

Thus, the primary motion of Kit formed by the instability of large-scale vertical and horizontal motions, having been subjected to destabilizing processes through loss of moisture supply in passing over Luzon, now had led to the creation of secondary smaller whirls. These false-eyes were partly of dynamic nature, caused by the disorganization of Kit's kinetic energy, and partly of thermal type.

Here, then, was the eye of Kit, the first ever seen in its entirety. The WRSP/3 mission had been accomplished. The furor of Kit was now recorded on film. Kit was dying a normal death, but in her last gasping breaths she had provided scientists with a new area of interest. The WRSP/3 had also found an entirely new mission to perform. Through the cooperation of NACA and their willingness to utilize the U-2 in flights over typhoons the way had been opened for a better understanding of Nature's most disastrous storms.

* * *

Description of Figures

Fig. 1. - The path of Typhoon Kit through Luzon, Philippines. Along the path, shown by the continuous solid curve, the circles bearing tics represent fixes of Kit made by weather reconnaissance aircraft having penetrated Kit's eye. These fixes are labelled with the date, first the day in November, 1957, followed by the time in GMT. The picture of Kit's eye in Fig. 2 was taken at the easterly bend along the path near the center of this figure.

Fig. 2. - Vertically above the eye of Typhoon Kit. The storm center is located at 19°30'N and 123°35'E. This picture was taken at approximately 0422 GMT on November 14, 1957. It is an unconstituted mosaic of aerial photographs taken from the WRSP/3 U-2 aircraft. The U-2 traversed the center of the eye on a 235° heading. This traverse is the mid-vertical of this picture from top to bottom. Along this mid-vertical appears a 39 nautical-mile length of cloudscape. From top to bottom of this picture, the middle-third continuously depicts a nearly correct vertically downward view toward the sea and clouds below. From side to side, however, the picture falls gradually off toward the horizons. The left side of the picture is toward the west-northwestern horizon. At the time of this picture, which is approximately one hour and a half after local noon, Kit is headed northward, which is toward the top of the picture and slightly to the left (N.B. the compass directly in this figure). The large bowl-shaped appearance of Kit's eye is

approximately 30 miles in diameter. Kidney-shaped, the darkened strips are portions of the sea surface visible through cloud-free moats. A fetch of transverse sea waves may be seen in the fleur-de-lis shaped moat just to the left of the picture's center. The tops of the cloud turrets at the upper middle of the picture are at 48,000 feet. Along the right of the picture and curving counterclockwise in from the upper left corner is a sheet of high cloud. As this cloud spirals cyclonically into the eye's center, it appears to sink and dssipate, as part of an upper indraft ventilating the typhoon center. This high cloud is also represented by the dotted shading in Fig. 3. Congruent with this picture in Fig. 2 and having the same orientation and coverage, Fig. 3 shows also for the storm center the horizontal streamlines indicated by the apparent motion and structure of the clouds, as shown in this picture, Fig. 2.

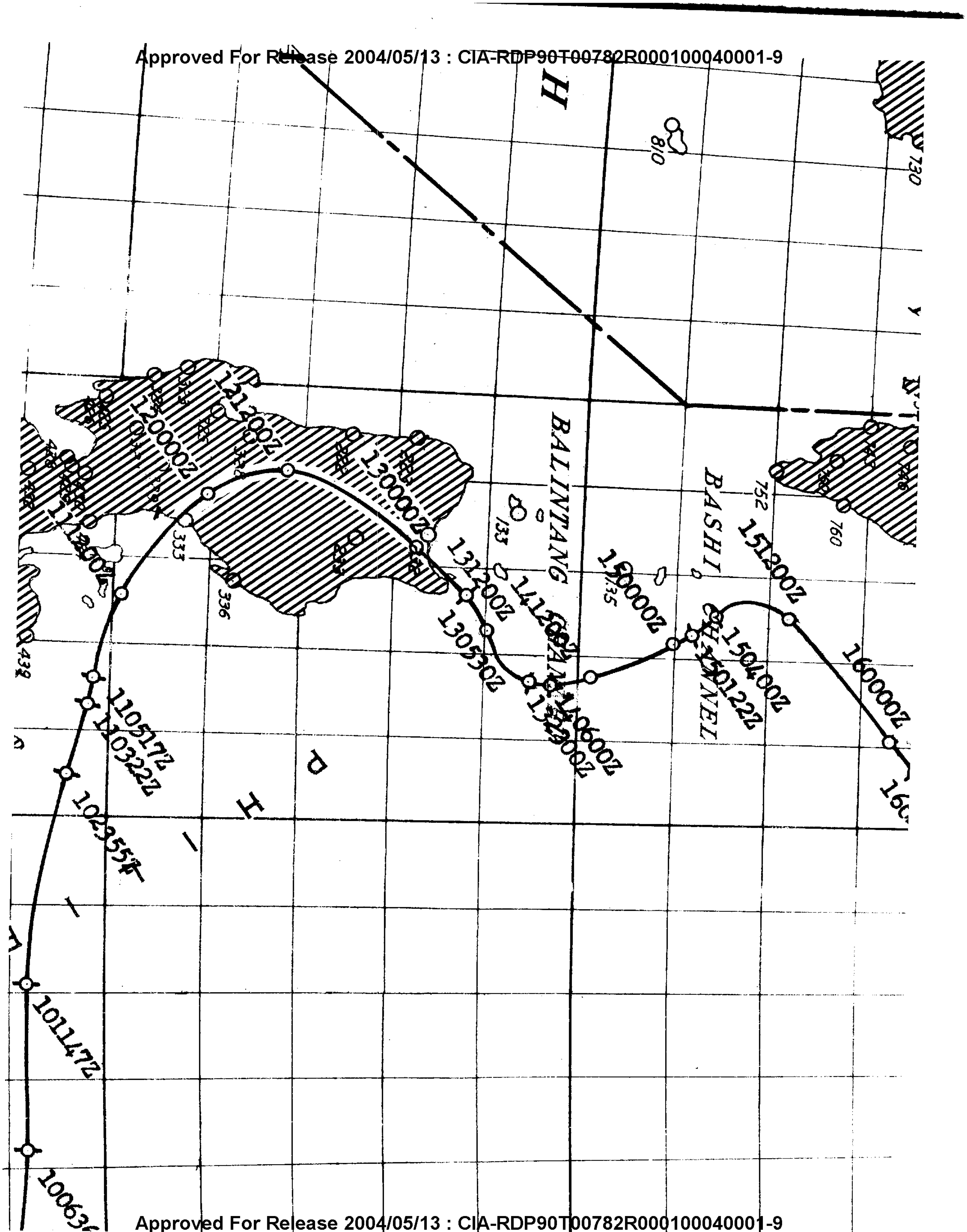
Fig. 3. - A horizontal steamline analysis made of the cloud picture in Fig. 2 for the eye of Typhoon Kit. This figure has exactly the same areal extent and orientation as Fig. 2. This figure shows that within Kit's eye there are nine small cyclonic swirls, maked by the "C's."

NOTE: It may be desirable to have figures 2 and 3 appear the same size in Weatherwise, opposite each other, for ready and direct comparison.

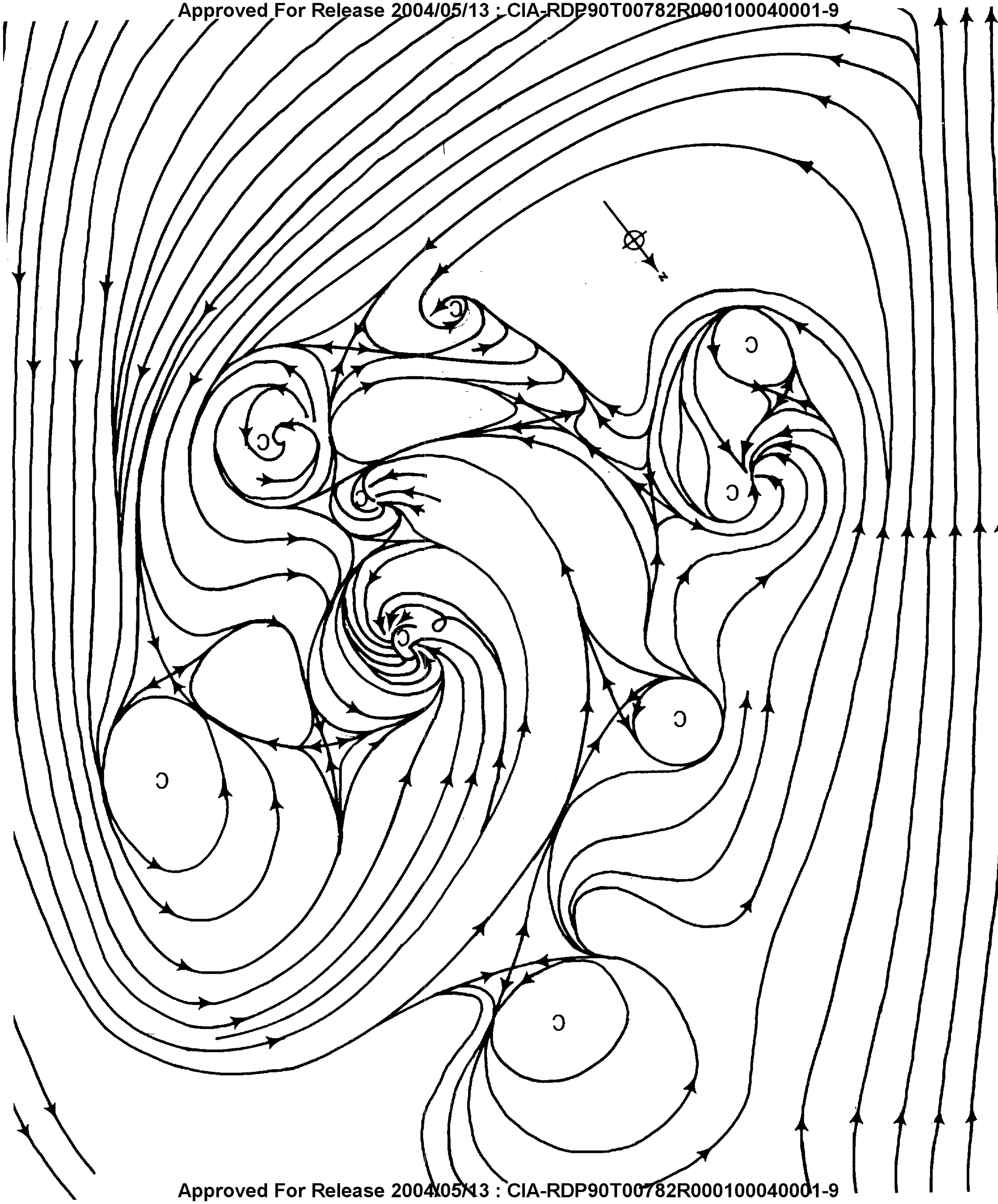
TABLE I

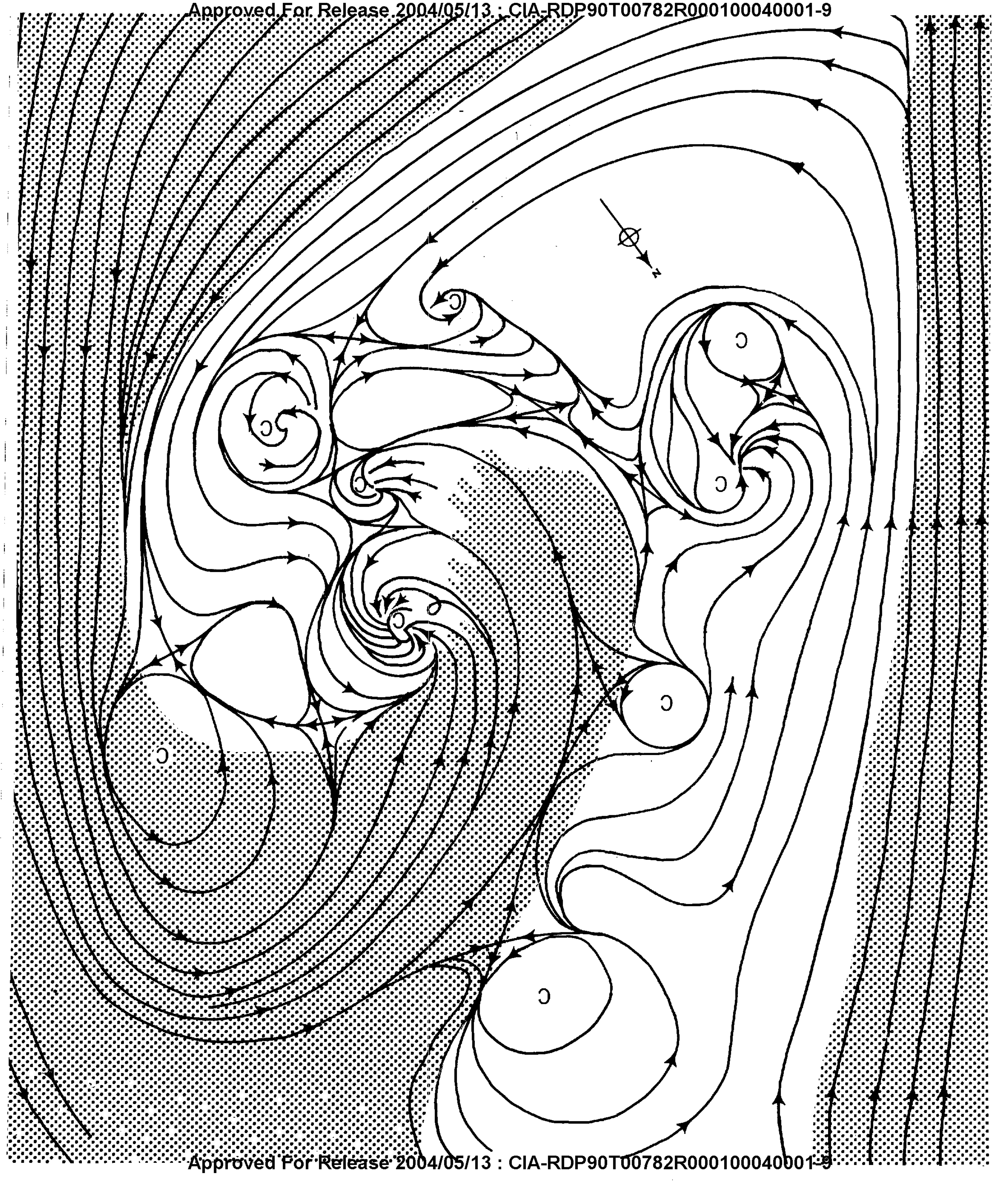
CONCISE WEATHER REPORT FROM THE PHILIPPINES IN CONNECTION WITH THE PASSAGE OF KIT

1. Barometric Minimum at MSL	937.0 mb at 0000Z, November 11, and 921.0 mb at 0600Z, November 11.
2. Maximum sustained winds:	
a. Over land	80 miles per hour at Virac, Catanduanes, and Casiguran, Quezon, at 2200Z, November 10, and 1600Z, November 12, resp; 100 miles per hour at San Vicente Quezon, at 1900Z, November 11.
b. Over water	200 miles per hour at 0600Z on November 11.
3. Maximum 24-hour rainfall	16.66 inches at Baler, Quezon, on November 12.



Approved For Release 2004/05/13 : CIA-RDP90T00782R000100040001-9

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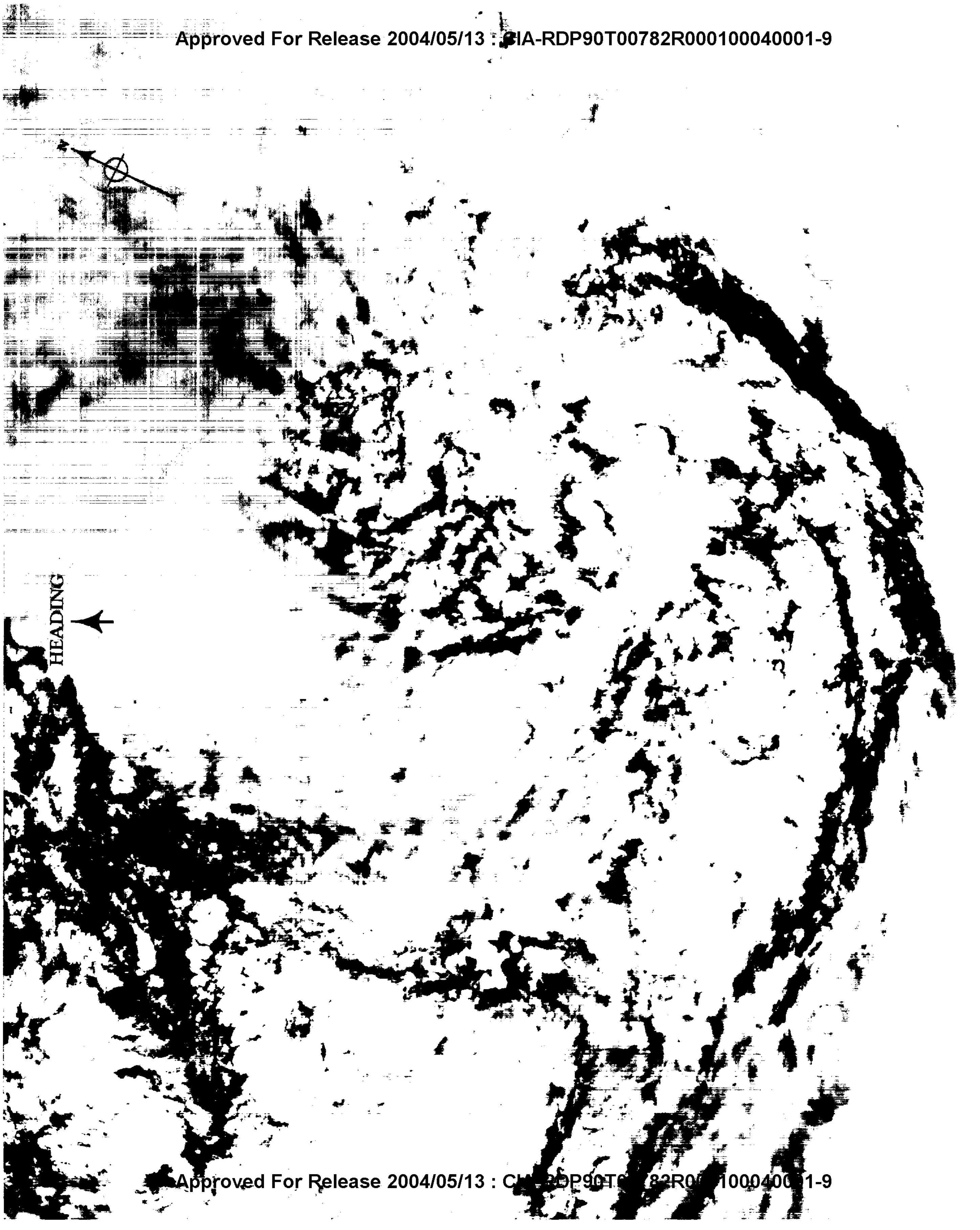
HEADING

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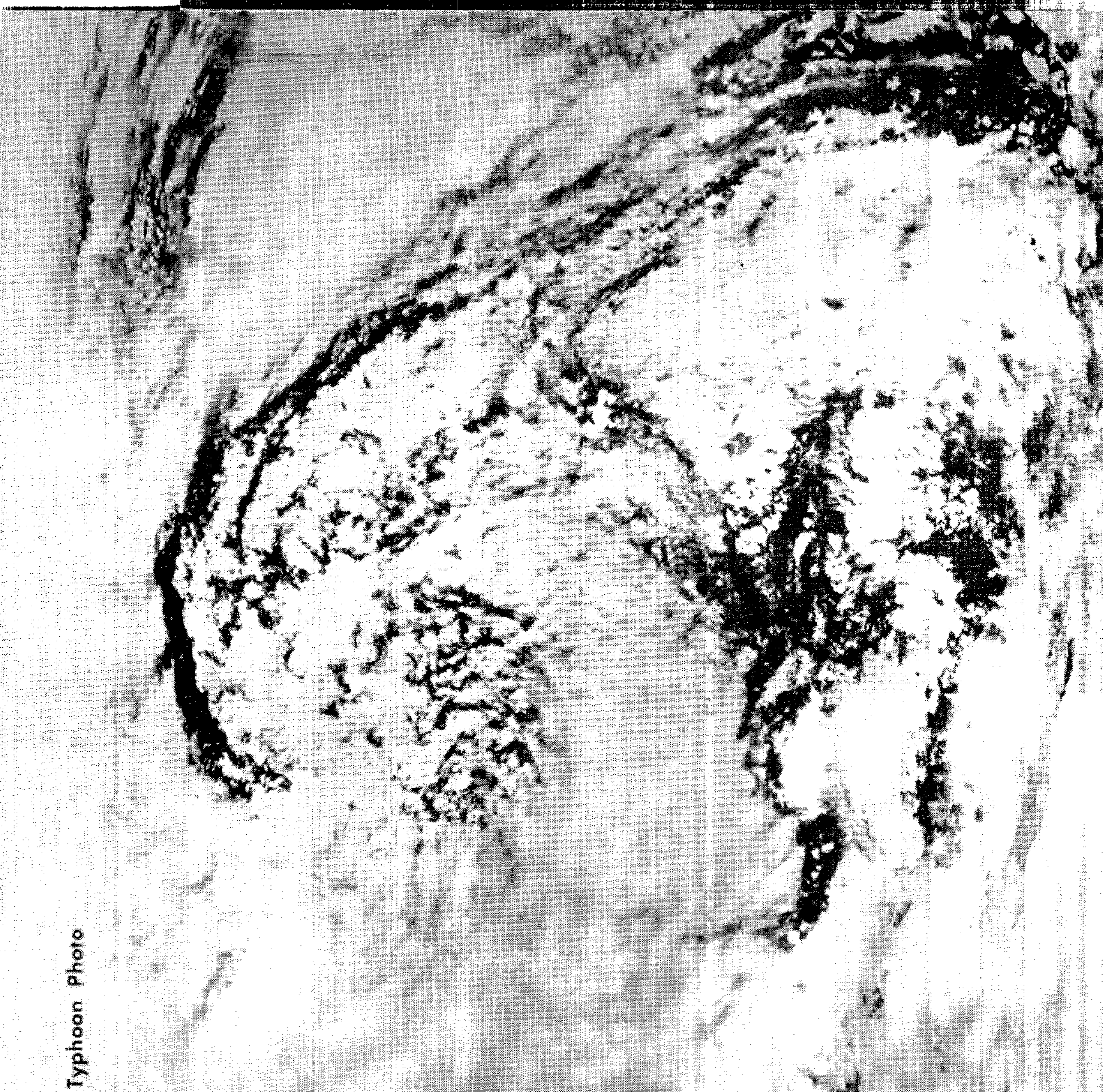
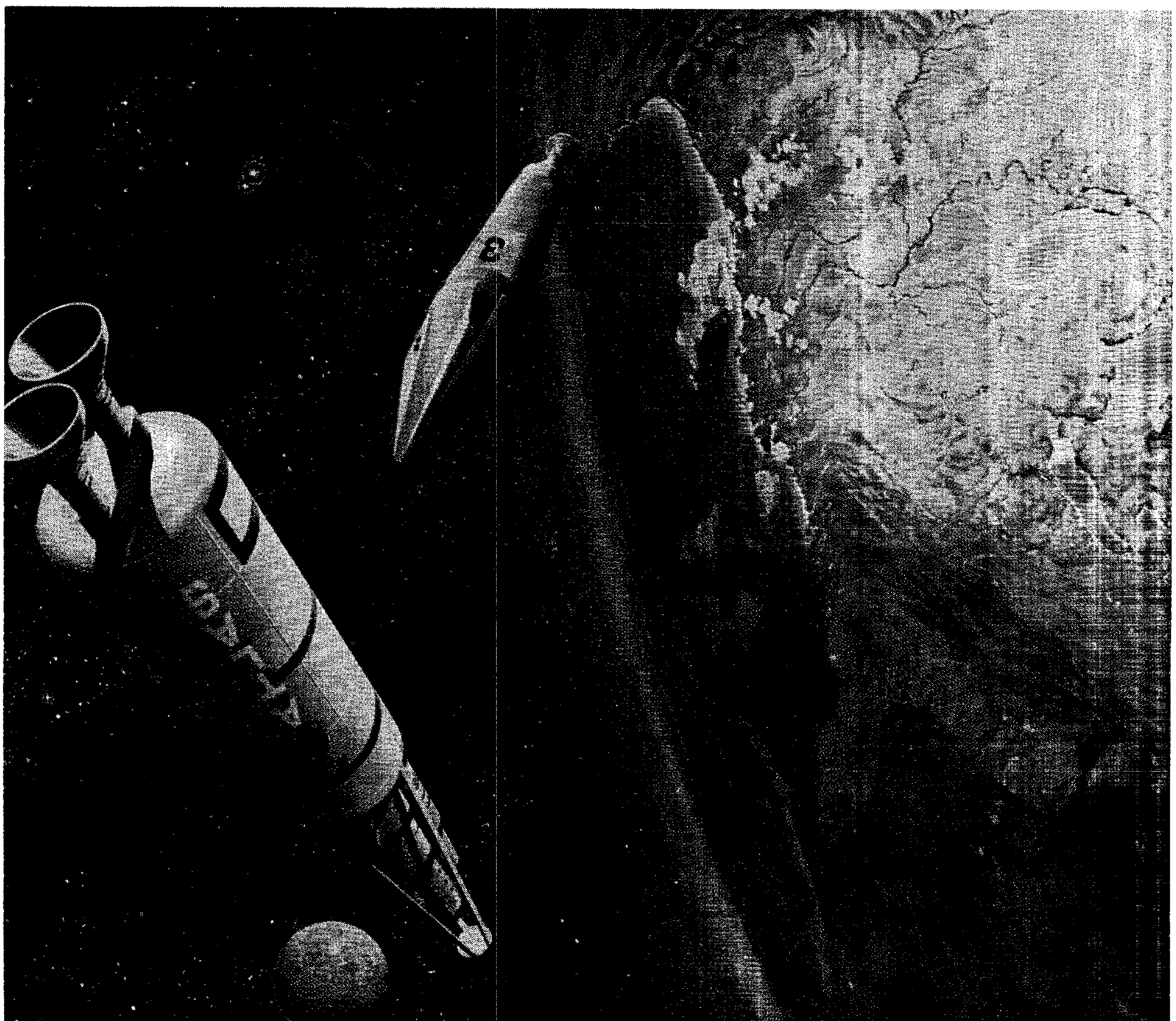
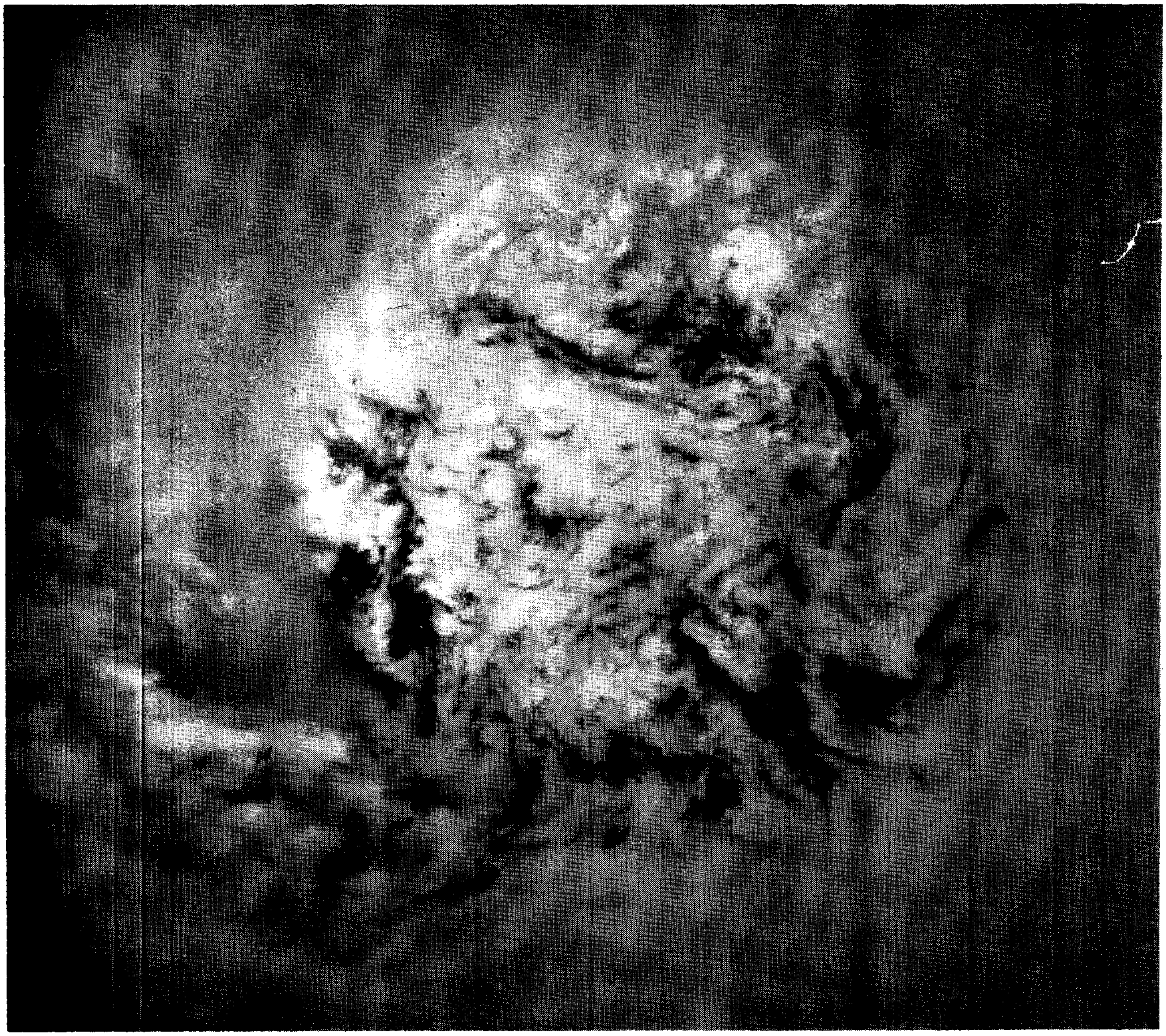


Typhoon Photo



Typhoon-Eye Cloud Patterns as Viewed from Above

ROBERT C. BUNDGAARD, ROBERT D. FLETCHER, JAMES R. SMITH



The Eye of Typhoon Ida from 50,000 ft.

Reprinted from WEATHERWISE, Vol. 12, No. 2, April, 1959

Typhoon-Eye Cloud Patterns as Viewed from Above

Robert C. Bundgaard, Robert D. Fletcher, James R. Smith
Air Weather Service, U. S. Air Force

Fig. 1. The eye of Typhoon Kit, with spiral bands and secondary vortices; 14 November 1957, north of Luzon.

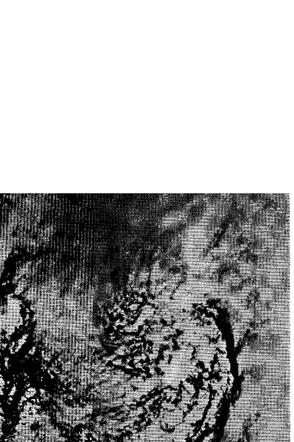


Fig. 2.

PRESUMABLY, one of the greatest immediate benefits of meteorological satellites will consist of presentations of large-scale cloud patterns of meteorological phenomena for use in weather forecasting and research. It is contemplated that patterns ranging in size from single convective-cloud developments to the collective cloud configurations of frontal systems will be recorded and placed at the disposal of the meteorologist.

In particular, it has been suggested that satellites will locate the centers of typhoons and hurricanes. Information as to the latitude and longitude of the eye of a storm, the character of the clouds in the vicinity of the eye and in the spiral bands surrounding it, and time changes in the cloud patterns, will be of tremendous assistance to the forecaster concerned with estimating the future position and extent of the storm. It will also be of great economic value to typhoon-reconnaissance people who no longer will have to search wide areas in locating a possible storm; but, instead, can direct aircraft to the exact location of the center to probe its lower regions for the wind, pressure, temperature, and precipitation data which probably will be beyond the measuring capabilities of satellites for some time to come.

The patterns of low-level winds and pressures in tropical cyclones are well known to meteorologists. So, too, are the cloud and precipitation distributions as determined by radar and by aircraft flying inside the various sectors of the storms. The important question has been raised, however, as to whether typhoons and hurricanes are really identifiable from above—from the vantage point of the satellite.

The National Aeronautics and Space Administration, with the support of the Air Weather Service, since 1957 has been conducting an upper-air research program in Japan for the purposes of testing new and improved types of meteorological sensing equipment and collecting high-altitude meteorological data. The equipment includes a Perkin-Elmer Model-501 tracking camera to record cloud patterns on 70-mm film. The equipment is mounted in a U-2 jet aircraft capable of flying at heights up to about 10 miles above sea level. Since November 1957 the aircraft has been able to fly over the tops of three separate typhoons and to photograph the cloud patterns of the centers. In each of the three cases the individual photographs have been fitted together into a mosaic showing the configuration of the clouds over the entire eye.

The first flyover, the details of which have been reported by Bundgaard, occurred on 14 November 1957 over Typhoon Kit just north of the Philippine island of Luzon. See *Weatherwise,* June 1959. Clearly evident was the general pattern of the clouds spiraling into the center, as was the location of the eye, itself. In the case of Kit, there appear to be several additional cyclonic whirls of which Bundgaard has identified eight.

On 9 July 1958 the Air Weather Service's 54th Weather Reconnaissance Squadron, under Lt. Colonel Dale Desper, noted on its synoptic charts a "suspicious area" about 300 miles northwest of Yap Island. The area was reconnoitered by WB-50 aircraft and by 11 July a full-fledged storm, Typhoon Winnie, was located. During the ensuing four days 13 penetrations at 500 mb were made into the center of the storm. On the 15th the typhoon entered Formosa—the most destructive such storm, for the island, of the past decade. Several hours before it reached the east coast of Formosa a U-2 aircraft was dispatched to the storm. It found it could top the clouds of the storm and did so, taking the pictures which form the mosaic shown in Figure 1. In overflying the storm the pilot reported a completely smooth ride, which was quite in contrast to the flights made some six or seven miles lower by the WB-50's which encountered severe turbulence. The eye was a large one; the typhoon winds of its circumference lashed the entire island. The photograph is of the eye itself with the wall clouds discernible in the very corners. The cloud pattern of the eye is very chaotic with two distinct layers clearly evident, one low and the other probably at cirrus levels. The photograph does not show the solid sheet of cirrus surrounding the eye. As described by the pilot there was no detail to this cirrus-cloud cover—only a "solid mist which extended to all horizons."

Fig. 3. The eye of Typhoon Winnie, with "wall" clouds discernible at edges of photograph; 14 July 1958, east of Formosa.

Typhoon Ida developed near the Mariannas on 21 September 1958. On the 22d it curved northward and passed over the Tokyo area near midnight of the 26th. When it was just south of Japan its central pressure reached a reported minimum of 877 mb and the maximum recorded wind was about 140 knots. It was a devastating storm which produced, incidentally, record-breaking precipitation in the Tokyo area. In Figure 2 is shown the track of the typhoon as well as its pressure pattern as it was approaching the island of Honshu. On the morning of the 24th a U-2 aircraft reconnoitered the typhoon. As in the cases of Kit and Winnie, the aircraft found it could clear the cloud tops of Ida and locate the eye of the storm. It made a succession of passes over the eye, the pilot reporting a smooth flight as was the case with Winnie.

The photograph of Ida's eye is shown on the front cover. Here there is no question as to the general circularity of the eye; in this particular picture there is only a suggestion, however, of the spiral cloud bands. The photograph shows a chaotic deck of broken low clouds in the eye with no middle or high clouds except, perhaps, for a few cirrus wisps protruding inward from the north. From the top of the low clouds to the top of the cirrus is estimated to be five to seven miles. The sun's reflection from the side of the cloud wall and top of the low clouds is quite bright—considerably more so than is apparent from the amorphous cirrus of the surroundings. The brightness within the eye is consistent with reports of typhoon-reconnaissance meteorologists who say that they are often blinded upon breaking through the wall of the eye. It also suggests that the excessive reflected radiation may in part account for the abnormally high temperatures frequently reported in the eye of a typhoon or hurricane.

From the three flyover photographs considered in this paper a few tentative conclusions can be drawn as to future satellite observations of typhoons and hurricanes:

1. Usually, although not necessarily always, the spiral structure of the clouds around the eye will aid in locating the center.
2. Usually the eye itself will be identifiable, although at times the existence of secondary vortices will require study by a trained analyst.
3. Usually there will be clouds within the eye; they will be chaotic and broken, with patches of sea surface visible; usually they will be low and often there will be no high clouds.
4. At certain times of the day, and with a center essentially free of high clouds, the eye may appear to the satellite to be a circular region of maximum brightness imbedded in a large area of not-so-bright cloud cover.

Much study is required to determine the optimum resolution for pictures taken from a satellite. Certainly a resolution of one mile and probably one of five miles will suffice for identification of the great majority of hurricanes and typhoons, but a resolution of 50 miles will probably hide the detail necessary for distinguishing the eyes and spiral cloud patterns. Further overflies will be made and more detailed data will be collected to assist in answering this and other important meteorological questions. In an overall sense, the over-the-top photographs of Kit, Winnie, and Ida indicate that cloud structures of hurricanes and typhoons are such as to make the satellite an excellent reconnaissance vehicle for their detection and location.

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NASA MEMO 4-17-59L

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MEMORANDUM

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

Langley Research Center
Langley Field, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON
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MEMORANDUM 4-17-59L

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

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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 L
obtained from operations over Turkey and Japan, and additional data have 1
been obtained from the operations over Western Europe. The combined 9
sample of data on atmospheric turbulence for the four operations presently 7
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

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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
L and also for the combined data sample. Table IV gives the frequency
1 distributions of gust velocity by 10,000-foot altitude intervals for the
9 four geographic areas of operation and also for the combined data. In
7 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.

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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.

<u>Variation with altitude</u>.- 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.

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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

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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

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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

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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

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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				
	aUS	bE	cT	dJ	Combined data	aUS	bE	cT	dJ	Combined data	aUS	bE	cT	dJ	Combined data	aUS	bE	cT	dJ	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

aUS Western United States.
bE Western Europe.
cT Turkey.
dJ Japan.

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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

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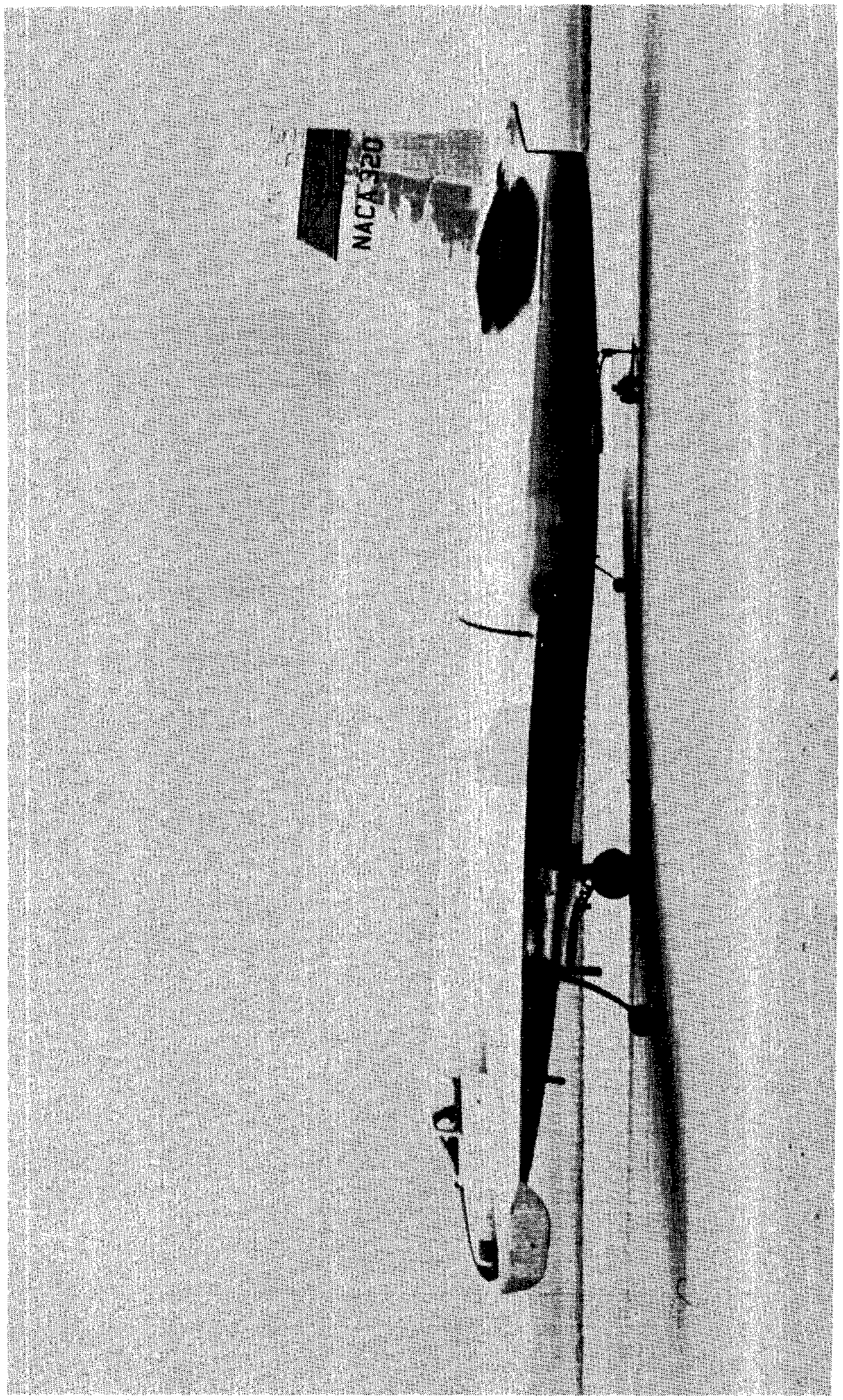

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Figure 1.- Test airplane.

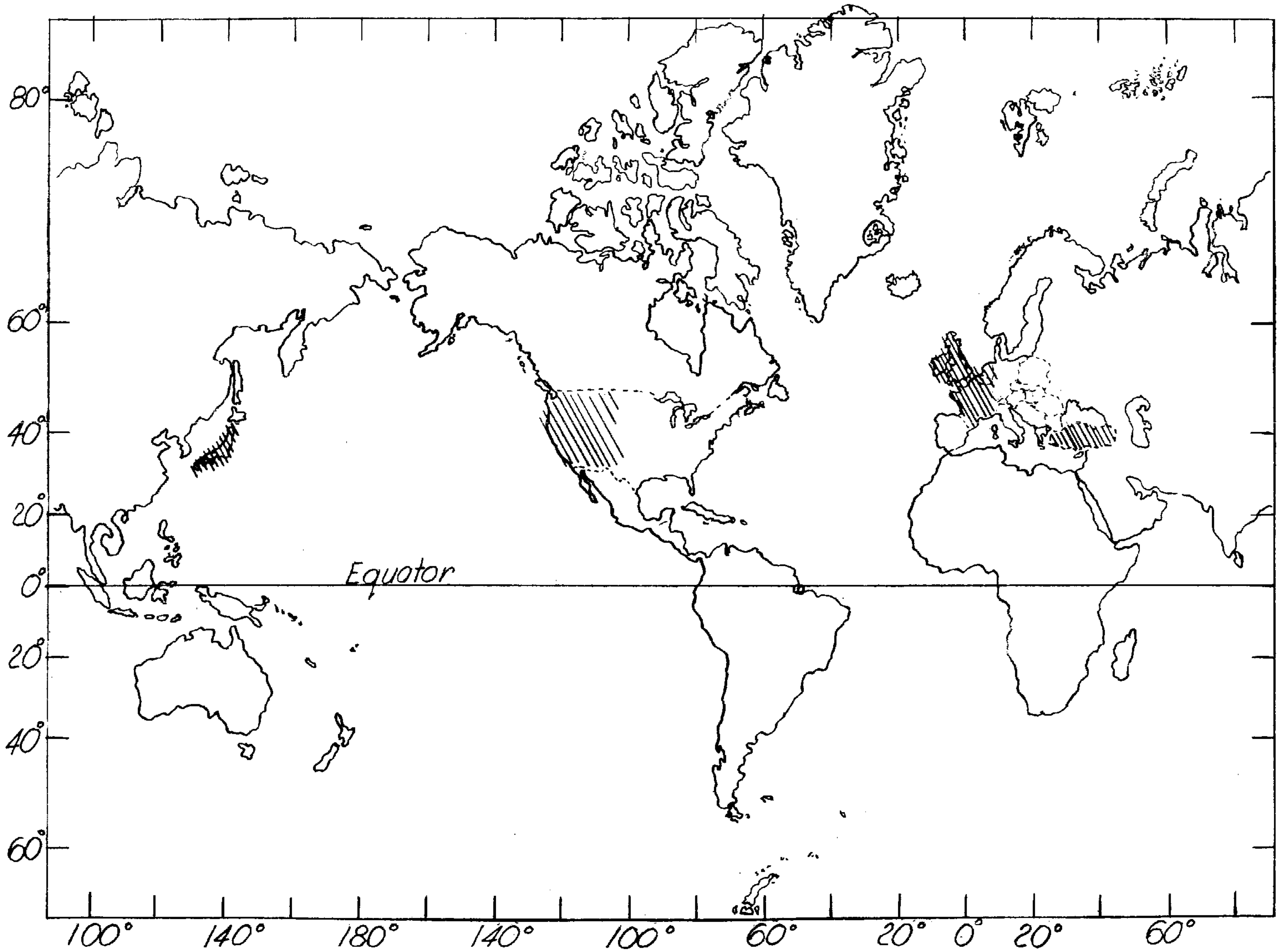

Figure 2.- Geographic areas (shown cross-hatched) sampled during four operations.

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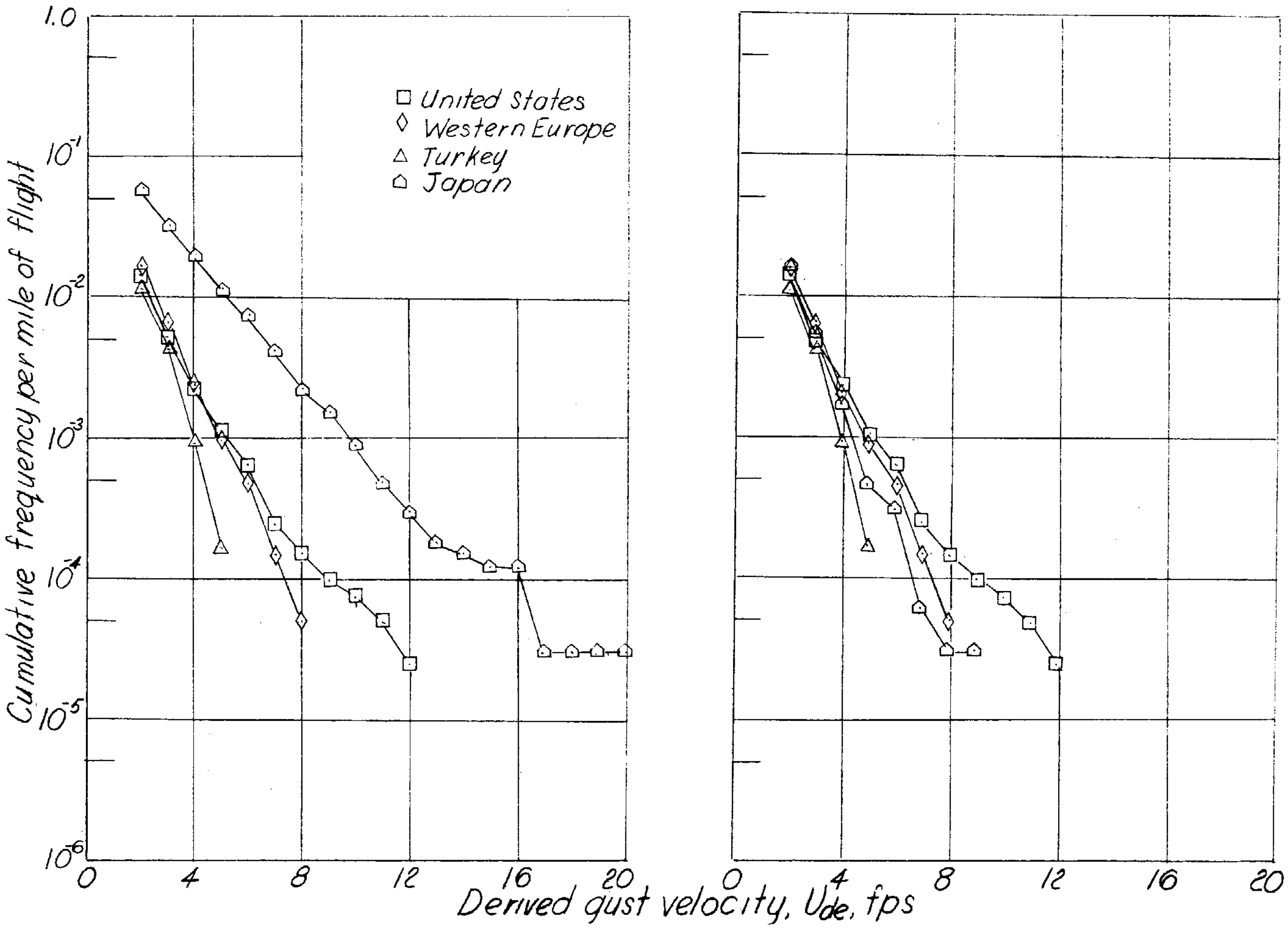

(a) All data.

(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.

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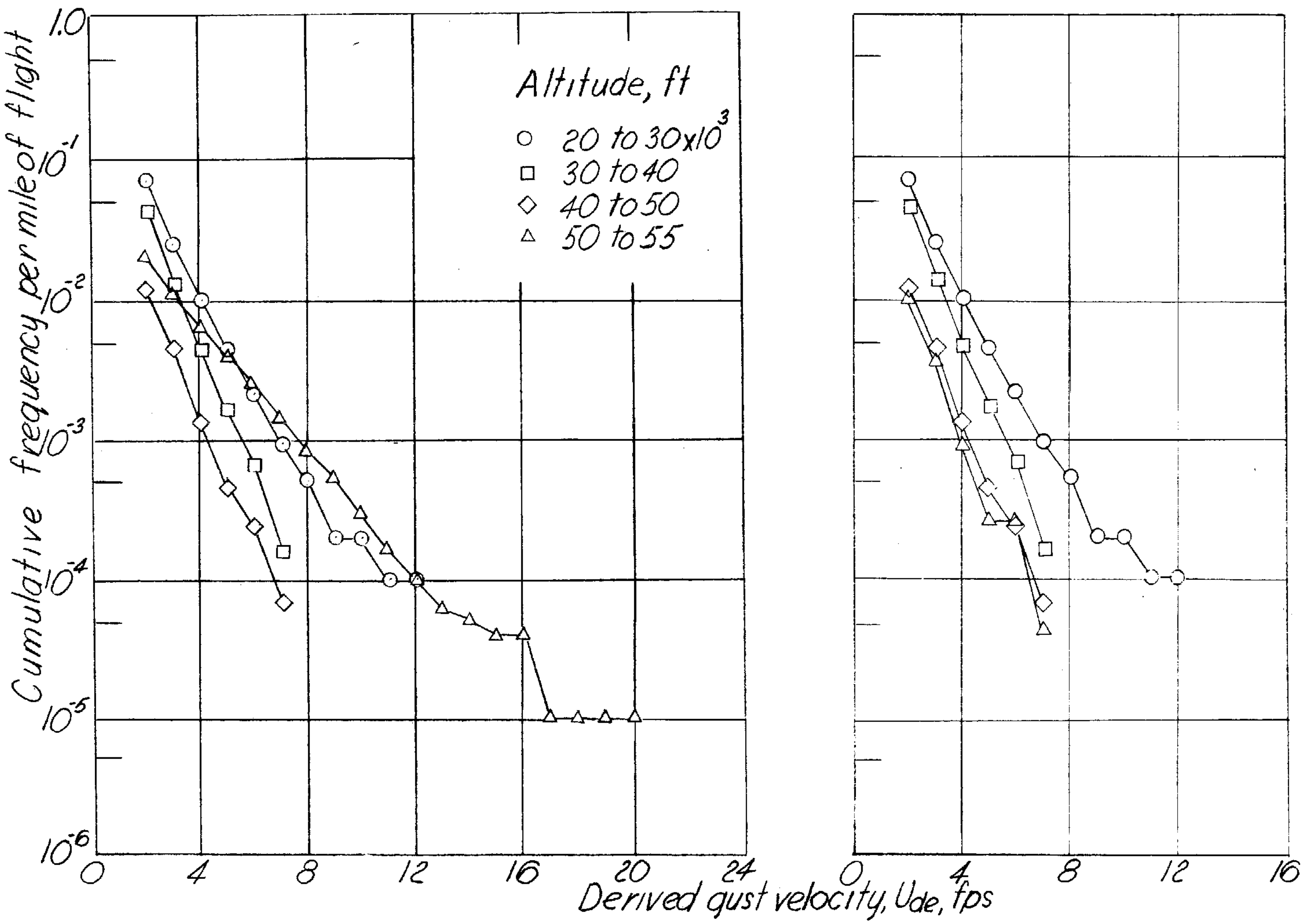

(a) All data.

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

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

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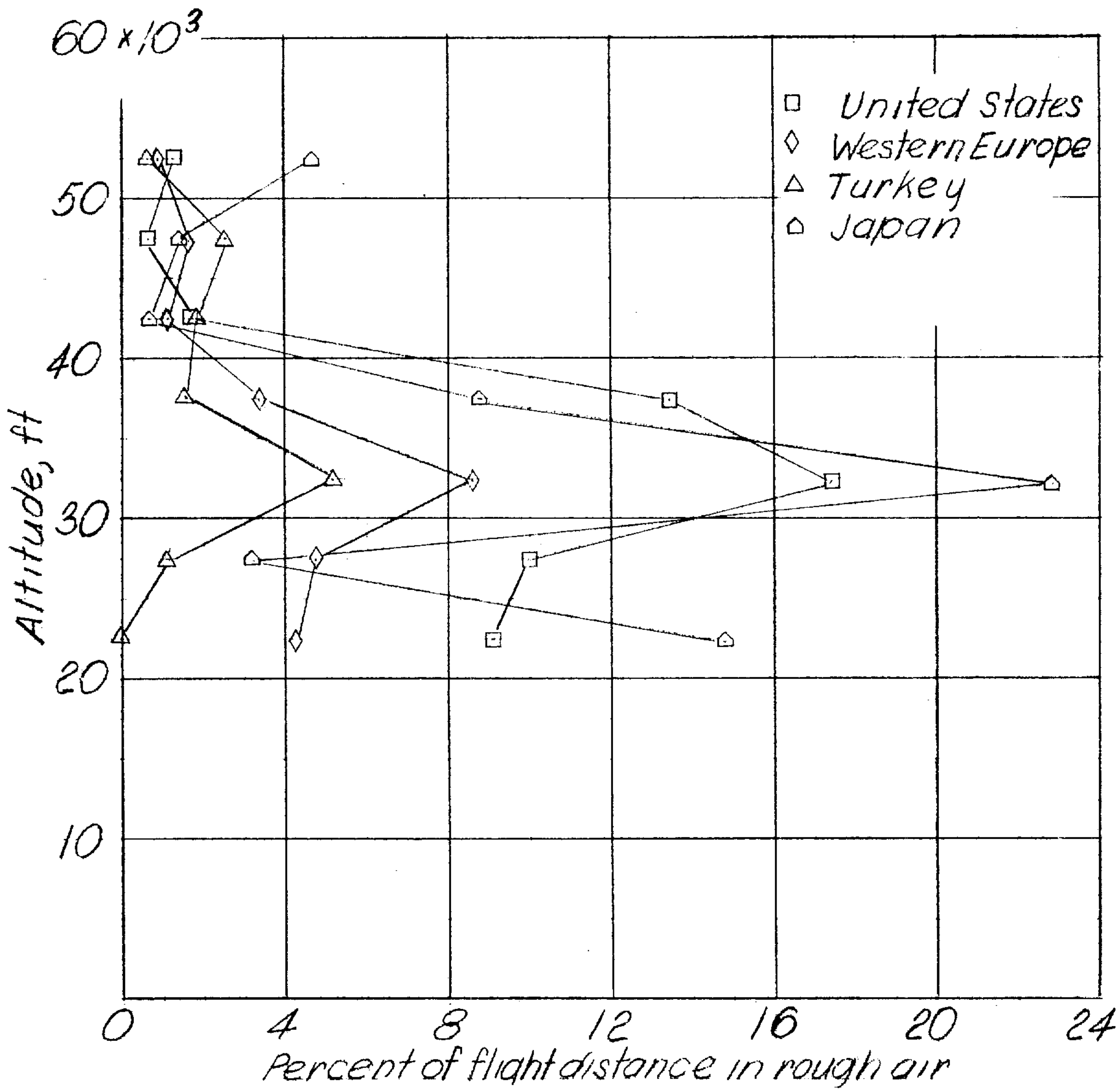

Figure 5.- Percent of flight distance in rough air (clear-air turbulence) at various altitudes for four geographic areas of operation.

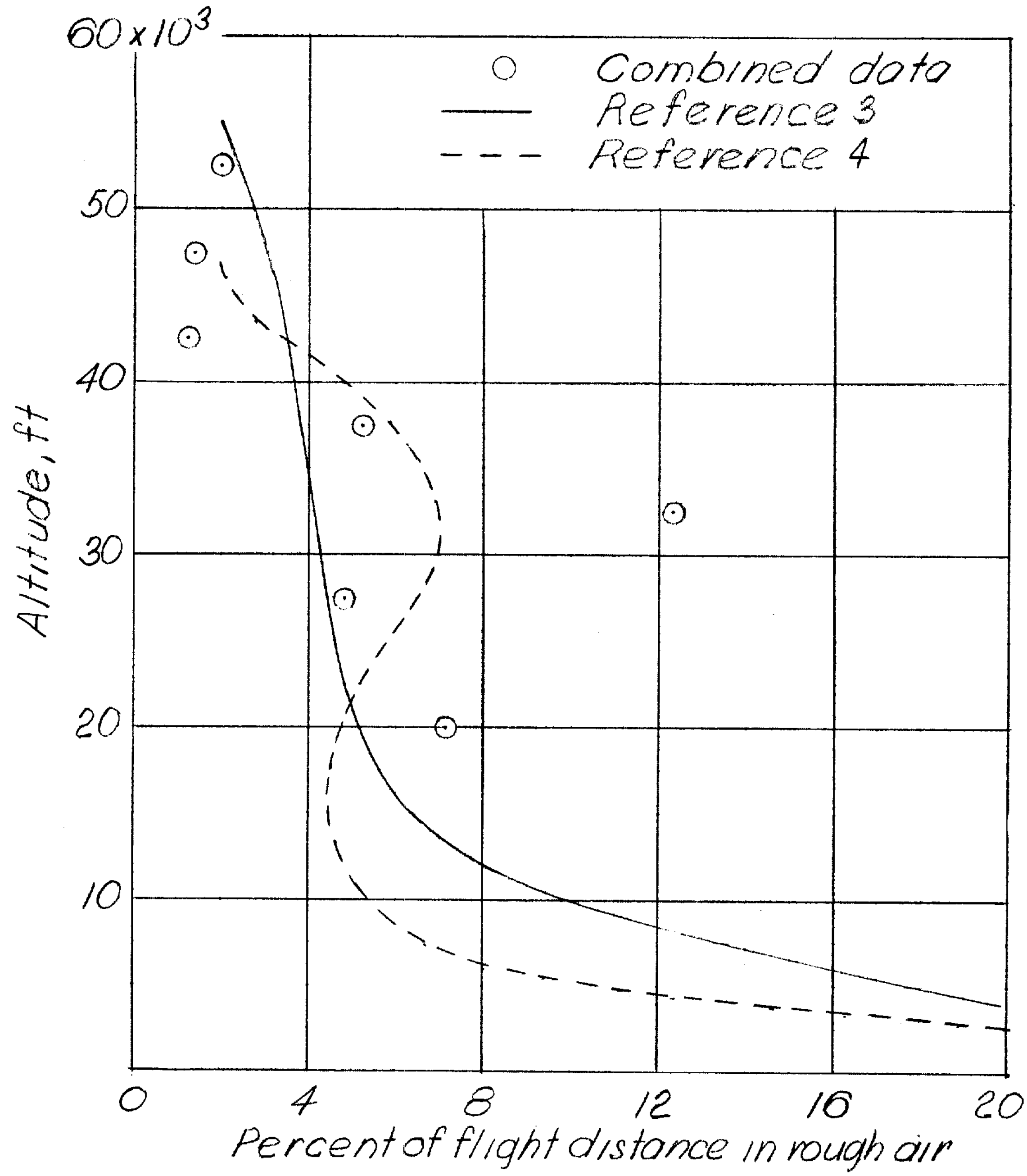

Figure 6.- Comparison of percent of flight distance in rough air at various altitudes.

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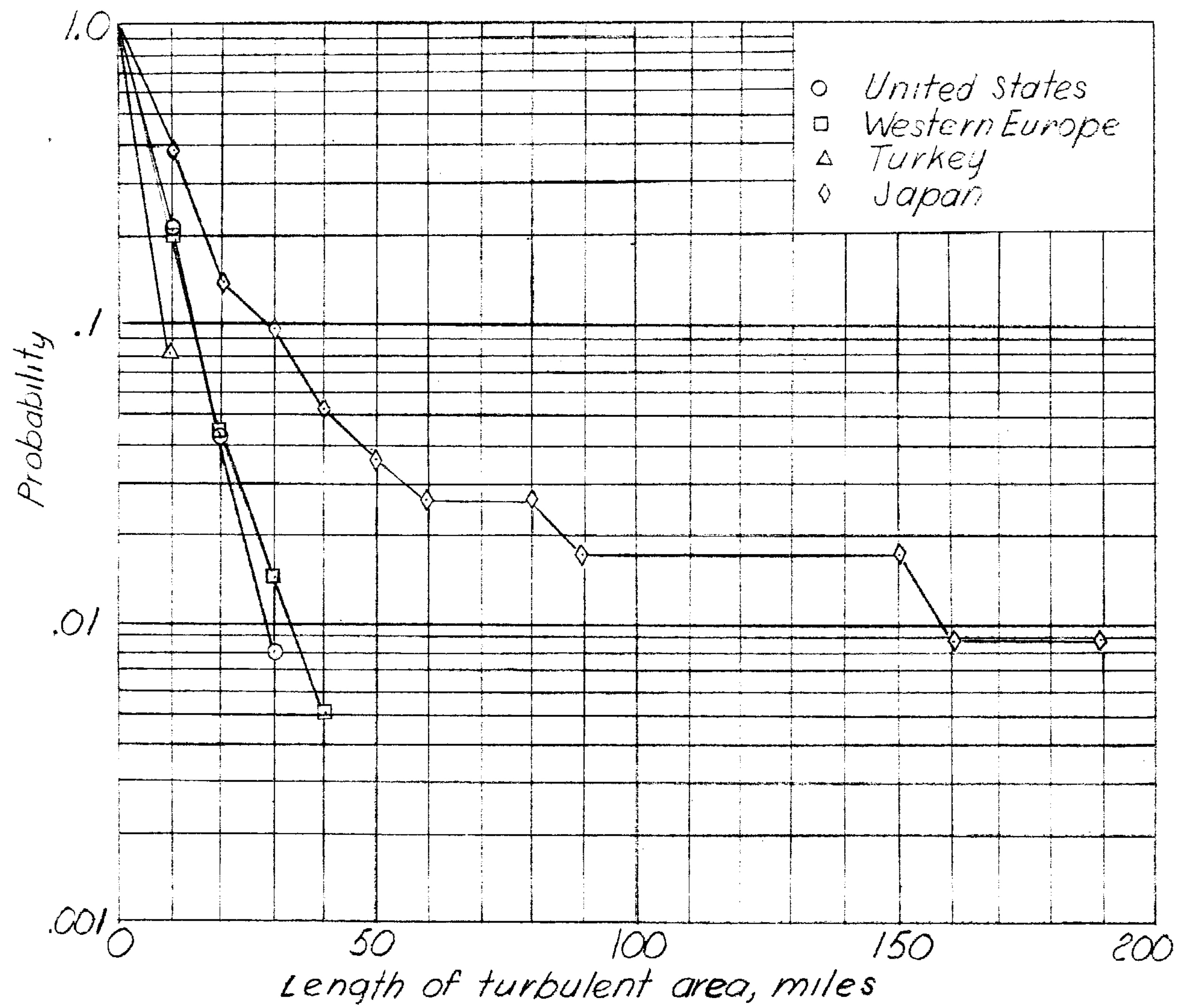

Figure 7.- Probability that length of turbulent area will exceed a given value.

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National Aeronautics and Space Administration.
AIRPLANE MEASUREMENTS OF ATMOSPHERIC TURBULENCE AT ALTITUDES BETWEEN 20,000 AND 55,000 FEET FOR FOUR GEOGRAPHIC AREAS. Thomas L. Coleman and May T. Meadows. June 1959. 21p. diagrs., photo., tabs. (NASA MEMORANDUM 4-17-59L)

An analysis is presented of data on atmospheric turbulence obtained from VGH records taken on Lockheed U-2 airplanes during research flights covering approximately 150,000 miles at altitudes between 20,000 and 55,000 feet over four geographic areas: Western part of the United States, England and Western Europe, Turkey, and Japan. The gust experience for the four geographic areas is compared and the variations in the gust frequencies and the percent of flight distance in rough air with altitude are indicated. The results on the variation of the percent of flight distance in rough air with altitude are compared with previous estimates.
Copies obtainable from NASA, Washington

1. Loads, Gust - Wings (4.1.1.1.3)
2. Gusts, Atmospheric (6.1.2)
3. Operating Problems (7)
I. Coleman, Thomas L.
II. Meadows, May T.
III. NASA MEMO 4-17-59L

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