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ATMOSPHERIC TURBULENCE IN RELATION TO AIR NAVIGATION

RESEARCH PROGRAMME AND DEVELOPMENT OF DESCRIPTIONS FOR USE IN REPORTING

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FOREWORD

Recognizing that more information regarding gustiness at high levels was needed in connection both with the forecasting of gustiness and with the development of airworthiness standards taking adequate account of gust factors, the third Session of the Meteorology Division, held in 1950, recommended a program of research which included arrangements for collecting data from the crews of civil aircraft and the development of turbulence measuring devices for use in radiosonde and radio/radar wind ascents.

The fourth Session of the Meteorology Division, held in 1954, simultaneously with the first Session of the Commission for Aeronautical Meteorology of the World Meteo ological Organization, reviewed recent work in this field and found that, although much remained to be done, progress in the independent research carried out by States had been promising; however, the scheme for obtaining turbulence reports from civil aircraft had largely failed. The Meeting therefore made the following recommendations, aimed at encouraging the continuance of turbulence research, improving the turbulence reporting scheme and stimulating interest in this scheme among both airline operators and meteorologists:

"Research on turbulence and gusts

Recommendation No. 41 - It is recommended that:

1) WMO encourage Members to continue research on the distribution of turbulence and gusts both geographically and with altitude and also on the physical structure of these phenomena and to send reports or progress to the WMO Secretariat, which should circulate the information to Members and make copies available to ICAO for circulation among aeronautical (non-meteorological) interests;

2) WMO be asked to consider the need for the preparation of a consolidated summary showing the progress made by Members in research on turbulence and gusts, and describing the methods employed."

"Turbulence reporting program

Recommendation No. 42 - It is recommended that:

1) ICAO be requested to maintain the high level turbulence report form (ICAO model) in its present form with the deletion of the NIL box

and the addition, in lieu thereof, of the following note: 'A report of the non-occurrence of turbulence will be indicated by endorsement on the air-report (AIREP or POMAR) for all flights above 7,500 m (25,000 feet).';

2) ICAO, in co-operation with WMO, urge States to seek the closest co-operation between meteorological services and airline operators in obtaining from aircraft commanders reports on turbulence experienced during flight including NIL reports;

3) ICAO, in co-operation with WMO, urge States to request operators to arrange for the turbulence report form to be supplied to the aircraft commander in respect to any flight flown at or above 3,000 m (10,000 feet);

4) ICAO, in co-operation with WMO, request from States that meteorological services and airline operators apply the following procedure for obtaining turbulence reports:

a) if a forecaster includes in his forecast the possibility of turbulence in clear air, for a flight to be made between 3,000 m (10,000 feet) and 7,500 m (25,000 feet) above MSL, or the possibility of turbulence in either cloud or clear air for a flight to be made above 7,500 m (25,000 feet) above MSL, he will specifically, at briefing, ask the pilot to complete the turbulence report form if turbulence as specified above is experienced. When considered necessary, the forecaster will attach a turbulence report form to the forecast documentation;

b) if, contrary to the forecast issued, an aircraft commander experiences turbulence in clear air in the case of a flight between 3,000 m (10,000 feet) and 7,500 m (25,000 feet) above MSL or turbulence either in clear air or in cloud in the case of a flight above 7,500 m (25,000 feet) above MSL, he will complete a turbulence report form;

c) NIL reports are required from aircraft commanders who do not experience turbulence during the course of flights made above 7,500 m (25,000 feet) above MSL. Such reports will be supplied by the endorsement "NIL TURBULENCE" on the air-report (AIREP or POMAR) form, completed during the flight. In the case of a NIL report, the aircraft commander will indicate on the air-report the type of aircraft, its position and indicated airspeed at any of the standard hours (0300, 0900, 1500, 2100) for upper air ascents which fall within the time of flight;

d) after the flight, aircraft commanders will hand in to the destination meteorological office the turbulence reports form together with air-reports containing reference to NIL turbulence; when sending turbulence reports to the collecting agency, the meteorological office will include NIL reports, whenever possible on the turbulence report form, extracted from air-reports."

"Comment

Aircraft reports of turbulence, including NIL reports, in the case of flights above 7,500 m (25,000 feet) above MSL are required so that a detailed analysis may be made associating turbulence or its absence with the synoptic situation and such parameters as Richardson's number, the horizontal shear, etc. All reports from aircraft commanders will be valuable, but a special importance will attach to those relating turbulence or no turbulence to the times when upper air soundings are made."

The meeting discussed mountain waves and, believing it to be desirable that aviation meteorological services pay more attention to these phenomena in all their aspects and not merely to the turbulence associated with them, made the following recommendations:

"Monograph on mountain waves

Recommendation No. 43 - It is recommended that:

WMO be asked to compile a monograph on mountain waves summarizing present knowledge regarding these phenomena as an aid to meteorological offices in providing improved service under this head."

"Comment

Although the discussion of the mountain wave was undertaken by the Meeting under the Agenda item on turbulence, it was recognized that a number of phenomena other than turbulence, associated with the mountain wave, were of great operational significance. A comprehensive monograph on the subject, containing an up-to-date account of the knowledge acquired by both theoretical and observational investigations was considered to be urgently needed."

The same Meeting also tried without success to develop a more refined classification of turbulence than that currently in use for reporting from aircraft (which is limited to "light", "moderate" and "severe" with no indication of frequency of occurrence). The following recommendation was therefore made:

"Turbulence classification for aircraft reports

Recommendation No. 44

ICAO, in consultation with States, continue studies on the classification of turbulence for aircraft reports so that eventually a more refined classification than the existing one may be introduced."

"Comment

The Meeting agreed that some indication of the frequency of turbulence experienced by aircraft was desirable, but no decision was reached concerning the precise form in which the existing classification should be altered."

A related subject discussed by the Meeting was the definition of "gust". This arose from a request received by ICAO from the World Meteorological Organization for a definition of "gust of importance to aviation". The request referred to wind near the earth's surface and was made in connection with the design of anemometers. However, at the invitation of the Air Navigation Commission, the Meeting discussed the subject from a more general point of view and, in the hope of clarifying further thinking on this subject, put forward a set of definitions of the parameters which it believed to be significant in connection with structural strength and controllability of aircraft. It also recommended that the values of these parameters of importance for the operation of aircraft be established in order that they might be taken into account in determining the criteria to be used in reporting gusts. The following recommendation of the Meeting was framed in such a way as to establish a clear-cut distinction between these two aspects of the subject, namely the definitions of "gust" and related parameters on the one hand and reporting criteria on the other:

"Definition of "gust" and of parameters needed to describe gust structure; operationally significant values of these parameters

Recommendation No. 45 - It is recommended that:

1) the following definitions be considered by WMO with reference to the problem of the fluctuations of the wind:

Gust - a departure, within a specified period of time, of the horizontal component of the wind velocity from its mean value (see paragraph 2 of the Comment);

Gust amplitude - the greatest value of a gust between two consecutive zero-values of the gust;

Gust formation time - the time taken by a gust to reach, within a specified time interval, its greatest maximum value (gust amplitude), from the immediately preceding zero-value;

Maximum gust lapse - the maximum difference in speed, in a specified period, between a maximum and the next minimum;

Gust lapse time - the time interval between the maximum and the minimum defining the maximum gust lapse;

Gust frequency - the number of gust maxima (absolute and/or relative) within a specified period of time;

Gustiness component (in a given direction) the difference between the maximum and the minimum speed, in the direction considered, divided by the horizontal mean wind speed;

Gustiness - the degree of turbulence as measured by the gustiness components.

Note. - In accordance with WMO Specifications, the 'mean wind' in the preceding definition is taken to be the average wind velocity over an interval of 10 minutes.

2) ICAO be requested to establish, in consultation with States and operators, the values of the parameters defined in 1) above, both the absolute value and the value relative to the mean wind, which are of importance for the operation of aircraft, especially near the ground, and inform WMO of the results to be taken into consideration for establishing the reporting criterion for gust."

"Comment

1) The 'definition' of gusts contained in Resolution 131 of the Conference of Directors, Washington, 1947, is in fact a reporting criterion. The above recommendation makes a distinction between

a) the definition of 'gust' and of various parameters needed to describe the structure of gusts;

b) the reporting criterion, i.e. the statement of what parameters should be included in wind reports and what is the range of values within which those parameters become important enough to be reported.

The second part of Recommendation No. 45 refers only to controllability of aircraft near the ground, since it is the lowest layer of the atmosphere which is of interest to WMO for the purposes of Resolution 131 of the Conference of Directors, Washington, 1947. For higher layers it is expected that aeronautical authorities will undertake similar studies of the problem in connection with the use of aircraft instruments on aircraft for the measurement of turbulence

2) When writing the definitions offered in the first part of Recommendation No. 45 the Meeting recognized the difficulties involved in the subject and the need for a reduction of the problem to its simplest possible form. The Meeting recognized that the word 'gust' is ambiguous. If, in a diagram

of speed versus time the values of the departures of the instantaneous wind speed from the mean over a certain period are represented, the term 'gust' may refer to:

a) any of the instantaneous values of the departure, or

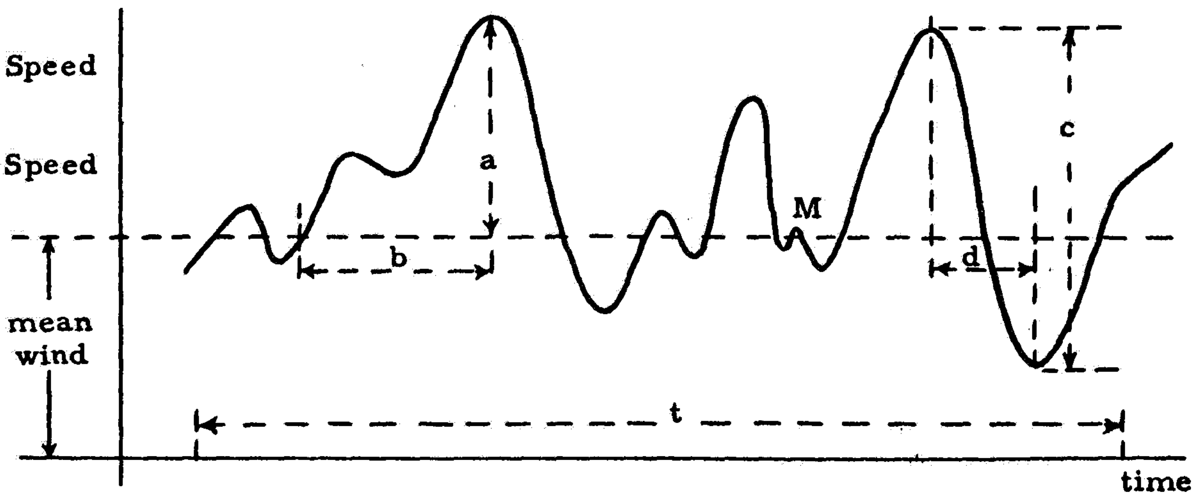
b) the section of the curve between two consecutive zero-values, or

c) each of the maxima (when the speed is greater than the mean) or minima (when the speed is less than the mean) of the curve, or

d) the absolute maximum (when the speed is greater than the mean) or absolute minimum (when the speed is less than the mean) between two zero-values, within a specified period.

The definition included in the first part of Recommendation No. 45 refers to either a) or b) and the context will make it clear, each time, which one of these two meanings is the one used.

3) Although any definition of a gust must take account of its vector properties, it is noted that meteorological observers, watching the variation of wind speeds on a dial, are observing and reporting, as gustiness, a scalar variation in the wind speed. An example of a diagram of wind speed versus time is given below, showing how the concepts defined in Recommendation No. 45, first part, are applied. (Only scalar values are considered.)



a - gust amplitude
b - gust formation time
c - maximum gust lapse
d - gust lapse time
t - the specified period of time to which the definition of the parameters refer."

"Note. - In accordance with Resolution 131 of the Conference of Directors, Washington, 1947, the following values should be considered for the reporting procedures:

a) the specified period of time (t) should be 20 seconds;

b) fluctuations like M, lasting less than 1 second, are 'filtered out';

c) the value of a (gust amplitude) is selected for reporting the gustiness, if greater than 5 m/s (10 knots); however, the value of 'gust' reported is not a, but the mean wind plus a."

Action on Recommendations 41 to 45 of the fourth Session of the Meteorology Division - first Session of the Commission for Aeronautical Meteorology

Of the recommendations quoted above, the Council of ICAO approved Recommendations 42, 44 and 45, part 2, and proposals for action along the lines indicated are in course of preparation. The World Meteorological Organization is taking action on Recommendations Nos. 41, 43 and 45, part 1.

Secretariat Studies

As a basis for the discussion of atmospheric turbulence by the fourth Session of the Meteorology Division - first Session of the Commission for Aeronautical Meteorology, the ICAO Secretariat prepared two working papers, one reviewing progress in the turbulence research program started as a result of action by the third Session of the Meteorology Division, and the other analyzing the problem of the development of an improved turbulence classification and reviewing relevant theoretical studies of atmospheric turbulence.

Various delegations expressed the opinion that these Secretariat papers ought to be reproduced in more permanent form to serve as sources of reference for the benefit of those working on these problems. The Air Navigation Commission, when reviewing the results of the fourth Session of the Meteorology Division, supported this view.

The two papers are therefore reprinted in the present circular, with slight editorial changes only.

SUMMARY

PART I

Recent work in the development of turbulence measuring equipment and in the experimental investigation of high level turbulence is reviewed and a brief account is given of associated theoretical studies. It is concluded that much remains to be done before satisfactory techniques for forecasting turbulence can be involved. Emphasis is placed on the need for improved methods of observing turbulence and for further theoretical studies based on the association of reported turbulence with the synoptic situation.

PART II

Atmospheric turbulence is shown to be characterized by a continuous spectrum which includes oscillations, or eddy motions, of all wavelengths ranging from the scale of molecular motions to the sizes of cyclones and anticyclones. Aircraft flying in a turbulent atmosphere respond only to oscillations within a very limited range of wavelengths. Recent theoretical and experimental advances in the field show that eddies in this region of the spectrum possess very simple analytical properties. Serious difficulties are found, however, in the exact definition and measurement of significant parameters in the velocity field. Problems connected with the definition of "gust" are stated with some detail. It is suggested that the complexity of the problems involved is such as to require that primary consideration be given to the clarification of the various problems and the adoption of a program of work to be carried out by States.

PART I

ATMOSPHERIC TURBULENCE RESEARCH IN RELATION TO CIVIL AVIATION

1. - Introduction

The MET Division, at its third Session, studied the information available at that time about gustiness at high levels and indicated that there was an urgent need for obtaining more data on turbulence experienced by aircraft in flight. The main emphasis was placed on the lack of accurate information on clear air gustiness, as a factor which had handicapped the forecasting of turbulence for high level flights and the drawing up of adequate standards in airworthiness.

Recommendation No. 2 of the third Session of the MET Division laid down a program with the purpose of collecting information on turbulence experienced by aircraft at high levels. The program, approved by the Council of ICAO, was established on the following basis:

a) A standard form of high level turbulence report, developed in consultation with States, should be filed for all flights above the 7,500 m level and also for any flights between 3,000 m and 7,500 m during which clear air turbulence was observed;

b) The forms, handed in either by the aircraft commander directly or through the operating agency to the meteorological office serving the arrival aerodrome, would be forwarded monthly by the Meteorological Authorities to the United States Weather Bureau;

c) The United States Weather Bureau would undertake the work of collecting and processing the reports and would make progress reports to ICAO and WMO from time to time; it would also provide summarized data, as it became available, to Meteorological Authorities on request.

Most Contracting States expressed their willingness to co-operate in the program. In a few instances Contracting States indicated that they had similar programs already under way and that they preferred to proceed with them, publishing the information whenever appropriate.

Up to the time of writing, no progress reports have been received and, therefore, no assessment can be made of the degree of implementation of the program agreed upon by Contracting States. However, since the third Session of the MET Division, a considerable number of studies has been published on the subject, showing that intensive work has been carried out in some States in the collection and analysis of aircraft reports of high level turbulence. This literature has furnished the only basis for an evaluation of the advances made in the field.

2. - The development of equipment for the measurement of high level turbulence

Besides outlining the program referred to in paragraph 1 above, Recommendation No. 2 of the third Session of the MET Division urged States to undertake research to develop equipment for use in both radiosonde or radio/radar wind ascents and on board aircraft.

With regard to turbulence measuring devices to be incorporated in routine radiosonde or radio/radar wind equipment, several States have reported that experimental research is under way, but no definite results have yet been notified. The available literature indicates progress in India, the United Kingdom and the United States, along different lines.

In Reference 16, Merewether and White report on research, carried out jointly by the United States Weather Bureau and the National Advisory Committee for Aeronautics, using a "gustsond". The following description is provided:

> "Basically, this is an instrument with a weight suspended on the end of a vibrating arm, the magnitude of the fluctuations of the arm depending on the severity of the turbulence. By means of radio, these fluctuations are transmitted to a receiver on the ground which transposes the signals into a smooth or wavy line according to the turbulence encountered. The instrument is borne aloft by balloon to a predetermined altitude where the balloon bursts and drops the instrument by parachute. It descends at a steady rate and transmits only on the way down. Since the release of the instrument is made at the time of radiosonde ascents, it is frequently possible to determine whether the turbulence occurred in clear or cloudy air. Currently, daily gustsond observations are being made at Caribou, Maine; Washington, D.C.; Miami, Florida; and Grand Junction, Colorado."

In the United Kingdom an investigation was undertaken to ascertain what information could be obtained from existing data on the variation of wind components in radar wind ascents. In Reference 20, Scrase reports on the analysis of the fluctuations, minute by minute, of wind components up to 30 km. In order to eliminate the fluctuations arising from errors of observation, he applied a technique due to Harrison. The results seem to be promising. As to the prospects for further work in this direction, the following statement is worth quoting:

"The present sounding technique, with eye readings at minute intervals, is not designed for the measurement of turbulent fluctuations in the free atmosphere but this investigation indicates that, with some improvements to reduce the observational errors, useful measurements should be obtainable. The chief need is for a higher degree of angular resolution, especially in elevation, in the wind finding equipment. Automatic tracking of the balloon should facilitate this and, when combined with automatic recording of the data, it should enable readings to be obtained at shorter time intervals."

The India Meteorological Department has developed an instrument called the "F-type radio-meteorograph" (Reference 24) which can be used to identify regions of clear air turbulence. It has a fan, made from a single sheet of paper, which is mounted in the instrument so as to rotate about a vertical axis when the balloon rises in the atmosphere. This fan rotates only when it moves relatively to the air in the upward direction, relative motion in the horizontal having very little effect and in the downward direction having none. It is maintained that this instrument can be a tool for locating regions of turbulence at any height in the atmosphere. This direct recording of vertical gusts cannot be obtained with any other available type of radiosonde.

Information on the structure of turbulence at high levels cannot be obtained either through the program referred to in paragraph 1 or by means of soundings of the types just described. Data obtained in these ways are useful for operational purposes and even for research connected with the development of forecasting techniques, but they do not satisfy the requirements of research connected with analysis of gust loads on aeroplanes. Airworthiness authorities have indicated the need for more information in this field. Recent developments in the mathematical techniques for theoretical studies of aeroplane behaviour and loads in rough air call for more detailed knowledge of the spectrum of atmospheric turbulence. This subject is considered further in Part II of this circular.

3. - Investigations of clear air turbulence

Since the third Session of the MET Division discussed the problem, early in 1950, the number of reports on high level turbulence encountered by aircraft in clear air has increased considerably. They have been the subject of special studies attempting to throw some light on the problem of determining the synoptic conditions which are favourable for the occurrence of turbulence. The most important studies available in the literature have been made in the United Kingdom by Bannon (Reference 3) and Hislop (Reference 12), in the United States by Harrison (Reference 11) and Mook (Reference 17), in Canada by Clodman (Reference 8) and in India by Sinha (Reference 21). Their results are summarized below.

In Reference 3, Bannon analyses seven reports of turbulence from jet aircraft over the United Kingdom. A detailed analysis is made of the synoptic situations over the three-day period covered by the seven reports. Cross sections of the wind and temperature fields show that the turbulence areas are located in the neighbourhood of a jet stream. In all but one case, the turbulence area lies on the low pressure side of the jet stream axis.

The paper by Hislop (Reference 12) reports on a clear air turbulence project carried out by British European Airways over the period January 1948 to January 1950. Mosquito aircraft were used and logged a total of 556 hours' flight time covering 92,300 miles. Twenty cases of clear air turbulence were found on nineteen flights during the period. Whenever gusts of 0.2 g or more were encountered, a search of the turbulence area was conducted to determine the thickness and horizontal extent of the turbulence layer and the horizontal and vertical temperature gradient in the area.

In the reports of clear air turbulence collected during the course of the project, the crew emphasized the absence of visual warnings. The bumps appeared to follow one another faster than in convective clouds and gave a hammering effect like "being in a fast car suddenly running over a series of deep unseen ruts in a road". There was no appreciable height change, probably because positive and negative accelerations followed in succession. Wing dropping occurred on only two occasions, which suggests that the eddies were usually considerably larger than the wing span of the aircraft.

The turbulence occurred in patches of varying thickness and horizontal extent, the averages being 3,000 feet and 50 to 100 miles, respectively. Ten of the twenty cases occurred within 2,000 feet of the tropopause. No consistent correlation was found between turbulence and wind speeds. The speeds ranged from 5 to 150 knots with 90 per cent of the cases below 75 knots. On the other hand, it was considered that vertical wind gradient was an important factor, if not the principal cause of the turbulence, and that Richardson's criterion was applicable (see paragraph 4 below).

In the United States, Harrison, of United Airlines, found (Reference 11) that moderate to severe clear air turbulence above 15,000 feet was associated, in all cases available to him, with a jet stream or a cold low, and with marked changes in both temperatures and wind speed in the horizontal.

The study by Mook (Reference 17) contains the results of a survey conducted by the United States Weather Bureau in co-operation with the National Advisory Committee for Aeronautics, throughout the year 1951 and part of 1952, to collect data on the occurrence of turbulence encountered by aircraft in clear air. Out of 241 reports received in 1951, eleven were about severe turbulence in clear air. Constant pressure charts of 300 mb were drawn to find the location of turbulence areas in relation to the jet stream. In those cases where upper wind observations were available near the places indicated in the reports, it was found that the turbulence layer was characterized by considerable vertical shear.

An attempt to relate areas of clear air turbulence to frontal zones has been made by Berggren (Reference 5) in connection with his proposed model of upper troposphere and lower stratosphere fronts. Analysis of one instance of clear air turbulence found over South-east England showed that the areas where it was observed were within the frontal zone as analyzed by him in a vertical cross section through the region. Furthermore, Berggren questioned some of Hislop' results and suggested that the difference in time and altitude between the aircraft reports and the synoptic charts were not properly taken into account, resulting in a wrong location of the turbulence areas in relation to the frontal zones. The case of 22 October 1952, analyzed by Pothecary (Reference 18), clearly shows that the reported turbulence occurred within the frontal zone at 20,000 feet.

Clodman (Reference 8) has analyzed over 500 reports of high level turbulence covering the period December 1949 to March 1953, most of them over eastern Canada at heights ranging from 18,000 to 45,000 feet. The average thickness of the layers was 2,700 feet for the cases of light and light to moderate turbulence, and 3,500 feet for the cases of moderate and heavy turbulence. However, the greatest thickness reported was of 18,000 feet for a case of light turbulence. There is no indication in the paper as to whether the figures include cases of turbulence within clouds. On the whole, the Canadian data seem to agree with Hislop's and Bannon's results.

4. - Clear air turbulence and instability of atmospheric flow

The studies reviewed in paragraph 3 indicate that, except for those cases of bumpiness associated with thermal currents over hot land in summer or with eddies orographically induced, clear air turbulence develops in regions of pronounced wind gradients. The problem has both theoretical and operational significance. For the theoretical meteorologist, it is still a challenge to find a satisfactory explanation of the physical processes which are responsible for the eddy motion associated with the sharp concentration of high velocity winds. The papers referred to in paragraph 3 contain attempts to test several of the existing theories of instability of atmospheric flow but no conclusive results appear to be available yet.

Dynamic instability, Reynold's stresses and gravity waves are the sources where investigators have been seeking for causes of clear air turbulence.

Harrison suggests that wind shear in the horizontal is the most significant factor. Hislop attaches greater importance to vertical wind shear and advocate the idea that Richardson's criterion can be applied to account for the development of eddy motions. Bannon (Reference 4) states that "all that can be said is that most of the observations of severe turbulence near a jet stream were

were probably associated with large wind shear in the vertical but that it seems likely that a few cases were not associated with large wind shear in the vertical but with large horizontal wind shear". Mook points out that most of the data examined in the United States "seem not to disagree" with the conclusions of Hislop and Bannon, and indicates an instance in which turbulence was found in a zone of considerable horizontal shear and negligible vertical shear.

The search for the probable causes of the gustiness in clear air has met with serious difficulties owing to the lack of dynamic theories to account for the instability of the flow. Several attempts have been made to apply the criterion derived from the theory known under the names of "dynamic instability", or "Kleinschmidt's instability", or "Helmholt's instability" (see Appendix A) which, in its crudest form, gives, for stable flow, a maximum horizontal anticyclonic wind shear equal to the local value of the Coriolis parameter. The theory has not been found applicable. Firstly, the great majority of cases of moderate or severe turbulence were encountered in the low pressure side of the jet, i.e., in the region where the shear is cyclonic. Secondly, the cases of turbulence on the high pressure side of the jet did not occur in the region of maximum horizontal shear. (This last circumstance, however, is by no means conclusive, since the exact criterion of dynamic instability is much more involved and has not been applied to the analysis of reported turbulence areas; the problem is further discussed in Appendix A.) It should be mentioned that Arakawa (References 1 and 2) has put forward a theory which seems to give satisfactory results in the cases of turbulence in regions of strong cyclonic shear.

The idea that Reynold's stresses could be the primary cause of turbulence has been found applicable to a large number of cases with strong shear in the vertical. The criterion developed by Richardson in his work on stratified fluids is generally held, in most of the papers referring to the subject, to be a satisfactory explanation of the mechanism of clear air turbulence. However, it seems necessary to emphasize the following statement by Bannon (Reference 3): "... in the cases of severe gustiness it appears that both meteorological features which are favourable for the occurrence of turbulence were present" (he refers to horizontal, or isentropic, and vertical wind shears). "There is no way at present of determining which factor was the more important but ease of physical interpretation would point to strong wind shear in the vertical as the main cause of the gustiness." The lack of a comprehensive theory accounting for all the parameters which appear to be relevant to the phenomena is, therefore, evident.

Attempts to connect clear air turbulence with gravity waves in a stratified atmosphere have been made by several authors - Mook (Reference 17) refers to an explanation proposed by K.O. Lange, who attributed a case of bumpiness observed in clear air to changes in lift produced by varying wind speeds. The ultimate cause of the effect reported by the aircraft as "gustiness" would be, according to this theory, the existence of waves in a zone of pronounced shear associated with a subsidence inversion. Objections to this kind of explanation have been raised by Hislop (Reference 12) on the basis that it requires horizontal variation of wind speed of about four times the magnitude of the vertical gust to produce an equivalent change in lift. This argument does not seem, however, to be conclusive. Clodman (Reference 9) refers to the possibility of "horizontal gusts" as a cause of bumpiness, taking into account reports of pilots who found some cases in which a change of course resulted in a decrease or disappearance of bumpiness, whereas the return to the original direction of flight resulted in a renewal of the turbulence. The matter needs further investigation.

5.- Turbulence in clouds

Turbulence associated with cumulus or cumulonimbus clouds is very well known and does not present any features which need to be discussed in this circular. The most complete survey of the field is reported in Reference 7 which has become the standard source of reference.

Turbulence associated with layer types of cloud has been reported up to very high levels. Besides isolated reports from pilots, the only statistical analysis available in the literature is found in Clodman's report on the Canadian data (Reference 9) already referred to. All cases of turbulence considered therein are divided into three groups: Group A - cases of clear sky; Group B - cases of turbulent area at least partially in cloud; and Group C - cases where some cloud was close to the turbulent area. Cases associated with cumulus or cumulonimbus cloud were excluded. The results are summarized in the following table:

Group	A	B	C	Total
Intensities 1 and 2	200	51	59	310
Intensities 3, 4, 5 and 6	102	28	44	174
All cases	302	79	103	484
Percentages	62%	16½%	21½%	

Clodman concludes that "it would appear doubtful if the presence or absence of cloud plays an important part in most cases of high level turbulence".

6.- Orographically induced turbulence

The formation of standing waves on the lee side of a mountain is a phenomenon whose existence has been known and studied for quite a long time.

Already in the last century, Lord Kelvin and Lord Rayleigh were looking for a satisfactory theory of the process and thereafter a number of investigators have contributed towards the understanding of very simple models of "lee waves" produced by idealized isolated obstacles of analytically simple geometric shapes. The advances in the last few years have been considerable, but none of the proposed theories is yet within sight of becoming a useful tool in the hands of the forecaster. Here again, empirical research and the collection and analysis of aircraft reports offer the most fruitful means of obtaining knowledge which could find immediate application for operational purposes.

The most systematic survey of the conditions of the atmosphere in situations of well developed lee waves has been carried out in the Sierra Nevada region of California by the "Mountain Wave Project" (formerly known as the "Sierra Wave Project"), a research project sponsored by the Geophysics Research Division of the US Air Force Cambridge Research Center and executed by the Southern California Soaring Association, Inc., and the University of California at Los Angeles. The region where the operations took place is characterized by the presence of a spectacular lee wave formation under certain synoptic conditions. The project conducted exploratory glider flights in the Sierra Wave up to the region of the tropopause and even into the stratosphere. Among the objectives of the project the following are worth mentioning (Reference 22):

"a) To advance the theory and understanding of the phenomena of orographic standing lee waves;

b) To explore with slow flying sail-planes the structure and texture of the wind under these conditions;

c) To learn about the air navigation hazards, such as excessive turbulence and spurious altimeter influences, which such waves may hold for aircraft exposed to them."

Flight Reports of the Mountain Wave Project indicate the existence of turbulence at various heights. Cases of very severe turbulence were reported at 40,000 feet. The general qualitative results, summarized in Reference 22 as "some observations primarily for the guidance of airmen", may prove to be useful for operational purposes. They are stated as follows:

"a) A 20 knot wind, or more, within 45° of perpendicular to, and measured above the mountain barrier under stable air conditions, appears to be the principal clue to the existence of waves. This information is available from weather services;

b) The "signs" of a wave are the lenticular and roll clouds paralleling the mountain range, approximately perpendicular to the wind. The violence and strength of the wave are often commensurate with the size and depth of these signs, e.g., big, violent roll clouds downwind of the mountains mean a strong and mature wave, but small clouds do not always mean a weak wave. In fact, strong waves occasionally exist with no clouds at all;

c) It is safest to avoid the vicinity of the lower clouds, as usually the most violent turbulence is found in this region, especially below the cloud;

d) The strongest updrafts occur just upwind of the clouds, and the strongest downdrafts just downwind of them. These currents frequently have vertical velocities between 2,000 ft/min. and 5,000 ft/min.;

e) The air is usually quite smooth above the roll cloud; though it may be ascending or descending rapidly. An exception to this "rule" appears when high altitude turbulence, apparently associated with the jet stream occurs. Adequate oxygen equipment is frequently necessary in order to climb above roll clouds;

f) Downwind flight into the roll cloud should be made at low speed and at an acute angle to the cloud front through the thinnest or most broken region to minimize the sharp-edged gust effect. If possible, roll clouds should be avoided altogether;

g) Down currents of extreme violence are found close to the lee side of the mountains, as is sometimes indicated by the descending portion of the cap cloud;

h) Surface winds during wave conditions are usually variable in direction and velocity, or even dead calm in various parts of the valley, and frequently are in the opposite direction to the upper air flow. Areas of blowing sand should be avoided."

The results obtained with sail-planes need some careful analysis before they can be extrapolated to commercial aircraft. There is no indication, in the report referred to above, of any study of the sizes of the eddies to which the sail-planes are responsive. Conditions producing smooth up and down motion of the glider may produce bumpiness to commercial aircraft, whereas these may not react to small-size eddies producing jolts to the gliders.

7. - Conclusions

No satisfactory theory on the physical mechanism responsible for the creation of turbulence is yet available. Recent attempts have opened promising avenues of research, but it appears that a long time will still be needed for any theory to produce results which could be incorporated into forecasting techniques. The concepts of hydrodynamic stability or instability of atmospheric flow patterns would need to be revised. In particular, a clarification would be necessary of the evolution of instability waves, in order to distinguish between those processes leading to "organized" large-scale developments (such as troughs and cyclones) and those producing small scale eddy motions.

Until the time comes when the dynamics of atmospheric flow patterns are sufficiently understood, it will be necessary to rely entirely on observational material. Systematic comparison of reports of actual findings of turbulence areas with detailed analysis of the corresponding synoptic situation is still the most practical method of gaining experience which may eventually lead to the formulation of operationally useful rules. Full implementation of the program outlined by the MET Division at its third Session is, therefore, of the utmost importance.

The results of previous researches in the field, such as those referred to in paragraph 4, are not conclusive. Greater refinements in the theoretical tools which were applied and more accurate analysis of the synoptic situation seem to be necessary before any of the theories which have been tested could be accepted or rejected. Special attention should be paid to the limitation in space and time of the turbulence areas, which makes it particularly difficult to locate them within synoptic maps and cross sections.

It appears necessary to have a better knowledge of the behaviour of aircraft flying in various types of air flow. This would include an investigation into the possibility of standing waves of certain wavelengths producing a "bumpiness" effect similar to turbulent eddies. At the same time, the response of aircraft to various sizes of eddies should be further analyzed in order to ascertain to what extent aircraft may be used to study the structure of high level turbulence and, inversely, to what degree a particular type of instability motion is likely to be reported by aircraft as "turbulence".

The classification of turbulence adopted for the standard questionnaires, although useful for operational purposes and for research in forecasting techniques, cannot fulfill the needs of gust accountability for airworthiness purposes. Recordings of standardized turbulence indicators are essential for the analysis of gust loads on aeroplanes.

8.- Action proposed to the MET Division, fourth Session

It was suggested that the MET Division, at its fourth Session, might have an opportunity of analyzing progress made in the implementation of Recommendation No. 2 of its third Session, the objectives of which had still to be attained, and of evaluating the material which had been collected as a result of the program thereby established.

The assessment of the results obtained heretofore in the field might include the consideration of the following points:

a) The suitability of the form used for reporting high level turbulence for operational purposes;

b) The feasibility of detecting turbulence by means of radiosonde or radio/radar wind ascents on a routine basis at upper air observing stations;

c) The area covered by the data collected to date, and the need for concentrated efforts to obtain information in areas where data were scarce or absent;

d) The association of reported turbulence areas with synoptic conditions as shown in synoptic charts and cross sections, and the relation of turbulence to significant parameters such as wind shear, vorticity distribution, Richardson number etc.

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APPENDIX A TO PART I

Summary of theories relating to stability of atmospheric flow

1. In paragraph 4 a brief review was made of several attempts by investigators to explain clear air turbulence by applying some of the available theories of the stability of atmospheric flow. The studies referred to therein have suggested that various dynamic principles could be used as possible tools to account for the instability of the flow in the regions where moderate or severe turbulence, not within clouds, has been reported. The analysis so far carried out is by no means exhaustive and it appears, therefore, appropriate to indicate here the main lines which still seem to be open to further investigations.

2. Dynamic instability of zonal motions. - The theory of the so-called "dynamic instability" of atmospheric motions has been developed in its simplest form by Kleinschmidt for the case of geostrophic flow. An atmospheric motion in geostrophic balance is found to be dynamically unstable when the anticyclonic wind shear on an isentropic surface is greater than the value of the Coriolis parameter at that latitude. This criterion is only approximately correct. A more accurate criterion has been developed for balanced zonal motions in a series of investigations which started with the pioneer work of Helmholtz, Rayleigh and V. Bjerknes and was completed, in recent years, by Solberg, Höiland and others.

The theory reached its most elaborate form, as a tool to be applied in forecasting practice, in the paper by J. Holmboe (Reference 13). The theory applies strictly to a baroclinic circular vortex which undergoes "vortex-ring-perturbations", i.e., perturbations which are identical in all meridional planes. The stability is found to depend on the space distribution of the rotational - or "inertial" - stability (which is a function of the field of absolute vorticity) and the static stability (which is determined by the field of potential temperature). The direction of minimum stability (or maximum instability) is determined by the relative position of four vectors, namely, the centrifugal force, the pressure force and the logarithmic ascendents of the circulation and the potential temperature. When compared with the so-called "Kleinschmidt's criterion", referred to above, the exact theory shows that the wind shear which determines whether the flow is stable or unstable should not be measured along the isentropic surface, but rather along the direction of minimum stability which in general makes a significant angle with the isentropic surface. J. Bjerknes (Reference 6) has advanced the idea that instability of the type under consideration must be released in flat cells; the circulation within the cells would exchange momentum across the zone of unstable shear and thus lessen that shear. He points out that the existence of multiple tropopauses, near the jet stream, characterized by quasi-isentropy, could be taken as indirect evidence of the existence of helical cellular circulations. The relevance of this type of motion to the problem of turbulence experienced by aircraft near the jet stream is still open to question. More experimental data will be needed to determine whether or not this type of cellular motion, released by "dynamic instability" of the flow, is likely to be felt as turbulence by an aircraft flying in the region.

3. Stability of waves in a barotropic current. - The theory of perturbations in a flow pattern characterized by a curved velocity profile has only been investigated in recent years. Working independently, Fjörtoft (Reference 10) and Kuo (Reference 14) put forward, almost simultaneously, a theory of waves in two-dimensional motions of a barotropic atmosphere, which gives some clues as to the type of wind distribution which could be expected to lead to instability of a zonal flow. Their results can be expressed, in their simplest form, in the following way: -The necessary and sufficient condition for a perturbation of a two-dimensional barotropic flow to be unstable is that the vorticity of the mean motion shall have an extreme value (i.e., maximum or minimum). When applied to a zonal motion of a barotropic atmosphere on a non-rotating earth, the criterion simply means that instability waves always exist whenever the velocity profile of the zonal motion has an inflexion point. When the rotation of the earth is introduced it can be easily found that the criterion requires that the shear at the inflexion points be greater than a certain value depending on the latitude (see figure 9 in Reference 10). A well-developed jet stream satisfies this condition, more often on the low pressure side (cyclonic shear) with reference to the axis. It is not known whether any attempt has been made to test this criterion on actual synoptic conditions when instability has been reported to exist.

4. Physical interpretation of turbulent motions. - The above-mentioned theories are incomplete in the sense that they only provide critical values of the parameters involved in the so-called "unstable perturbations", but they do not give any clue as to the subsequent evolution of the "unstable waves". In particular, it cannot be decided whether the motion will be a large-scale organized wave of increasing amplitude, or will "break" into eddies of certain sizes. In fact, very little is known of the detailed dynamic characteristics of turbulent flow, beyond certain statistical features, and there is a considerable gap between the theory of stability of wave perturbations in an arbitrary flow and the theories of turbulent motion. The paper referred to under Reference 23 provides perhaps the only attempt which could be found in the literature to explain the physical mechanism of turbulence. The theory is very promising and may lead eventually to a better understanding of the dynamics of fluid motions. Preliminary work carried out by J. Holmboe at the University of California (unpublished) has further clarified the problem studied by Theodorsen. From these attempts it appears that a satisfactory solution cannot be arrived at without a comprehensive theory of three-dimensional motion. This approach may provide, in the not too distant future, some practical tools to be incorporated into forecasting techniques.

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PART II

CONSIDERATION OF THE POSSIBILITY OF DEVELOPING IMPROVED SPECIFICATIONS FOR THE REPORTING OF TURBULENCE FOR AVIATION PURPOSES

1. - Introduction

Part I of this circular contains a short review of various problems connected with turbulence experienced on board aircraft and of attempts to develop adequate techniques for its forecasting. The emphasis was placed on the relationship between regions where turbulence was found and the corresponding synoptic situation. The aim was to point out some significant parameters which could serve for the detection and forecasting of regions of turbulence.

The subject now needs to be approached from an entirely different angle. Leaving aside the question of where turbulence could be found and how it could be predicted, it is necessary to analyze the structure of the turbulent flow and to assess its effect on the operation of aircraft. Three aspects of the subject will be considered in this connection:

The response of an aircraft to a system of airflow disturbances (turbulence) characterized by a random function with a continuous spectrum of frequencies;

The properties of the turbulent flow within the range of frequencies to which the aircraft is sensitive;

The definition and measurement of appropriate velocity functions which are necessary to describe the structure of the flow in the range of significant frequencies.

The final aims of a study of the functions referred to above, in so far as aeronautical meteorology is concerned, would be:

To provide a classification of turbulence operationally satisfactory and physically sound;

To determine the extent to which the significant characteristics of atmospheric turbulence are dependent upon distance from the ground;

To lay down a set of specifications for recording instruments, in order to obtain the information necessary for operational and research purposes.

The problem of a turbulence classification was considered by the third Session of the MET Division and by the first Air Navigation Conference in so far as turbulence in the free atmosphere is concerned. The classification derived by the latter meeting combines simplicity and operational applicability, but it is considered to be an oversimplification of the problem.

The question of the specifications for recording instruments has recently been brought to the attention of ICAO. The Commission for Instruments and Methods of Observation of the World Meteorological Organization, at its first Session (Toronto, August-September 1953), reviewed the definition of "gusts" given in Resolution 131 of the Conference of Directors (Washington 1947) and adopted Recommendation No. 25, which is included in Appendix A (as also in Resolution 131, C.D. Washington, 1947). The Executive Committee of WMO, at its fourth Session, October 1953, decided to refer this recommendation to ICAO and to the Technical Commissions mentioned in the recommendation (Resolution 46; EC-IV). Accordingly, ICAO was invited to furnish a definition of "gust of importance to aviation", the main purpose being to decide, on the basis of the requirements of the various users, what are the desirable performance characteristics of anemometers.

The Air Navigation Commission studied WMO's request and decided to refer the matter to the MET Division for an analysis of the problems associated with the preparation of a definition of "gust of importance to aviation". The subject seems to have a natural place within the statement of the turbulence problems indicated above.

2. - Characteristics and scale of atmospheric turbulence

The characteristics of turbulence in a given region of the atmosphere are partly determined by proximity to the ground. The surface of the earth plays a double role with regard to the turbulence which develops in the lowest layer of the atmosphere, since the ground not only acts as one of the main factors - and sometimes *the* factor - responsible for the development of turbulence, but at the same time imposes certain restrictions on the type of motion which could be developed (since vertical velocity must be zero at the surface). At sufficiently high levels, on the other hand, the turbulent motion is determined entirely by the dynamic and thermodynamic properties of the flow. It is, therefore, customary to speak of "turbulence in the surface layer" and "turbulence in the free atmosphere" as two distinct types of atmospheric turbulence. The surface layer might also be divided into two sub-layers; in the lower sublayer turbulence increases with height, whereas in the upper sub-layer it decreases with height (*see* Reference 3).

A second important - and perhaps the most difficult - distinction to be made in dealing with the subject of atmospheric turbulence is related to the scale of the phenomenon. In fact, there is a continuous range of fluctuations in atmospheric flow which could be classified as "turbulence". They range, in space, from molecular fluctuations up to large scale synoptic phenomena; and, in time, from extremely rapid oscillations of the order of fractions of a second up to long period variations of the order of a climatic scale. As a result, no satisfactory definition of turbulence is yet known, and it is doubtful whether a definition could be found which covers all possible cases. In spite of this complication, the subject itself is sufficiently well defined. In general, and unless otherwise specified, only an intermediate scale of phenomena, where the "oscillations" have a period of the order of seconds and the space scale is of the order of metres or kilometres, is considered under the subject of "atmospheric turbulence".

From the vast field covered by the subject of turbulence, a restricted domain can therefore be singled out which has a definite scope. The "origin" of the eddy motion within this limited range might need to be explained with reference to either the whole field of turbulence or at least a considerable part of it. This problem, however, is the concern of the forecaster and it has been referred to in Part I of this circular. From the point of view of the effects of turbulence on aircraft, and for the measurements which are necessary to obtain a description of that part of the field which is relevant to the problem, it suffices to analyze the structure of eddy motions of a scale within a rather limited range. It will be shown that eddy motions which are of interest to aviation have fairly simple theoretical properties.

3. - Atmospheric turbulence and aircraft response

An aircraft moving through the atmosphere is a system under the influence of random disturbances. The system is sensitive to certain types of oscillations characterized by a limited range of frequencies. The oscillations of very long period are either counteracted by the pilot or result in a slow up and down motion which is not "felt" as turbulence. Oscillations of very short period, on the other hand, are "averaged out" by the size of the aircraft. If the motion of the atmosphere is visualized as a continuous spectrum of eddy sizes which range from the smallest disturbances near the ground up to large scale synoptic features, the preceding considerations indicate that aircraft are sensitive to eddies of certain sizes only. It appears that these eddies have dimensions of the order of 100 m.

The effect of atmospheric eddy motions on the aircraft is a change in the magnitude of lift and drag, resulting in changes of aircraft motion. Data concerning the structure of turbulence in the free atmosphere, within the scale indicated above, may be obtained by recording on board aircraft the changes in acceleration due to turbulence. There are two problems to be solved in this connection:

a) the experimental and/or analytical derivation of the behaviour of aircraft exposed to turbulence the characteristics of which are known;

b) the determination of the structure of turbulence from a knowledge of the response of an aircraft to turbulence.

A critical analysis of data available until 1950 on both of these problems has been made by Benthem in Reference 1. The author points out the vagueness and inconclusiveness of many results arrived at in the specialized literature in the field, and indicates the need for more precise definitions of the concepts involved. In particular, he emphasizes that the exact meaning of the concept of "turbulent air" utilized in various well known reports on research in the field is "all but clear". The difficulties encountered in making precise the meaning of this concept, and others related to it, will be set out below. However, it will be convenient to present first an account of some recent advances in the field of atmospheric turbulence which appear to offer a theoretical and experimental basis for a clearer understanding of the physical processes whose effects are intended to be measured.

4. - Theoretical advances in the knowledge of the structure of atmospheric turbulence

In the last few years considerable advance has been made in the study of the structure of turbulence. Current theories, which have been developed since the last world war, attempt to introduce physical ideas into the statistical analysis and have initiated a new approach to the problem which has already shown promising possibilities. The names of Kolmogoroff, Onsager, Weizsäcker and Heisenberg are prominent in these developments. Excellent reviews of the new trends and an analysis of potential and actual applications can be found in References 4, 6 and 8. Only a brief account of some ideas which seem to have a direct bearing on the problem of aircraft response to atmospheric turbulence will be given in this paper. In this connection, Kolmogoroff's similarity hypotheses are considered to be the most important step in turbulence research in recent years.

Kolmogoroff's model of turbulent flow can be described in the following way:

a) A turbulent fluid motion may be considered as a cascade process. Large eddies break into smaller and smaller ones until very small eddies are obtained which dissipate by the effect of viscosity. The whole motion may, therefore, be represented as the superposition of oscillations whose wavelengths constitute a continuous spectrum. Each oscillation is characterized by the wave number (i.e. the number of wavelengths per unit length). To each wave number corresponds a certain energy, so that the energy of the turbulent motion can be represented by the energy spectrum.

b) The energy of the eddy motion is taken from the energy of the "basic" motion and it follows a definite evolution. The very large eddies (small wave number) are fed by the energy of the basic motion. The energy supplied by the large eddies is passed on to the smaller ones until it is dissipated at the other end of the spectrum (very small eddies, i.e. very large wave numbers).

c) The transfer of energy from one region of the spectrum (i.e. a given size of eddies) to another far removed (i.e. eddies of very different size) is assumed negligible. Small eddies do not have, therefore, the characteristics of the larger eddies. After a certain critical wave number, the statistical properties of the eddies are thus independent of the basic motion. In particular, the statistical properties of the smaller eddies will be independent of direction; the motion in this region of the spectrum will be "locally isotropic".

d) The whole spectrum of turbulence is, according to the foregoing considerations, divided into two different regions characterized by anisotropy (large eddies with definite structure) and isotropy (small eddies with properties independent of direction) respectively. The region of isotropic eddies is subdivided into two sub-regions: the viscous subrange (very small eddies whose energy is dissipated into heat) and the inertial subrange (characterized by eddies which are both isotropic and independent of the fluid viscosity).

The theoretical importance of Kolmogoroff's description of turbulent motions lies in the simplicity of the laws which can be derived for both subranges of the isotropic region. MacCready (References 5 and 6) has obtained experimental data on the energy spectra of atmospheric turbulence at low elevations and his results indicate the validity of the formulae derived from Kolmogoroff's hypotheses. Measurements at 146 m over the ground would indicate that the inertial subrange includes eddies up to 139 m in diameter.

In Reference 6, MacCready indicates that "eddies of 100 to 150 m dimensions are very important for aircraft gust load considerations, and it is hoped the inertial subrange simplifications can be applied to such problems". A similar remark is made by Liepmann (Reference 4). It should be pointed out, on the other hand, that the theory of the inertial subrange of isotropic eddies seems to offer already a clear account of some findings reported by Donely in Reference 2.

Press and Houbolt (Reference 7) have analyzed data obtained by Clementson on the spectrum of turbulence in the free atmosphere. By using some modern developments in the mathematical theory of random processes, the authors have found that the curves of spectral distribution of energy coincide in shape with the curve derived from the energy of isotropic turbulence for wavelengths which correspond roughly to eddy sizes of 2 to 500 m. The results are applied to calculations of the effects of the position of the centre of gravity, low short-period damping and wing-bending flexibility on the response of an aircraft to gusts.

5. - The problem of defining and measuring significant parameters in turbulent flow, and the definition of "gust"

The analysis of the field of motion in a turbulent flow usually follows a method first used by Reynolds (1893). The whole motion is considered to be the super-position of two constituents: the "mean" flow and the "turbulent" flow. For this purpose, the following definitions of the velocity field are adopted:

Let $\underline{V}$ be the instantaneous velocity (vector) of the wind, and T a period of time centred at the instant t_o. The mean velocity $\overline{\underline{V}}$ is defined as follows (a line under a symbol will indicate a vector; a line above the symbol will indicate the mean value over the period T, as defined below):

$$\overline{\underline{V}} = \frac{1}{T} \int_{t_o - 1/2\,T}^{t_o + 1/2\,T} \underline{V}\, dt$$

Let $\underline{i}$, $\underline{j}$, $\underline{k}$ be the unit vectors along the co-ordinate axes x, y, z; and u, v and w the components of $\underline{V}$ along these axes. If the system of reference is oriented in such a way that $\overline{\underline{V}}$ is along $\underline{i}$,

$$\overline{\underline{V}} = \overline{u}\underline{i}$$

$$\underline{V} = u\underline{i} + v\underline{j} + w\underline{k}$$

where $u = \overline{u} + u'$, u' indicating the instantaneous departure of the wind component along $\underline{i}$ from the mean value $\overline{u}$.

The eddy velocity $\underline{V}'$ is defined by the relationship

$$\underline{V} = \overline{\underline{V}} + \underline{V}'$$

$$= (\overline{u} + u')\underline{i} + v\underline{j} + w\underline{k}$$

that is

$$\underline{V}' = u'\underline{i} + v\underline{j} + w\underline{k}$$

It is obvious that the value of $\overline{\underline{V}}$ may depend on the selection of T. In general, a certain range of values of T could be found, within which $\overline{\underline{V}}$ remains reasonably constant as a function of T. The lowest value of this range is then adopted for the definition of "mean" wind. In this case it follows that the mean value of $\underline{V}'$ over the period T is zero; i.e.:

$$\overline{\underline{V}'} = \frac{1}{T} \int_{t_o - 1/2\,T}^{t_o + 1/2\,T} \underline{V}'dt = 0.$$

Besides the ambiguity introduced in the definition of the mean that has been referred to above, new difficulties arise when the separation of the flow into a "mean" and a "turbulent" part is applied to energy considerations. Swinbank (Reference 10) and Priestley and Sheppard (Reference 8) have shown in a very clear manner the shortcomings of the method. They indicate that the separation of the kinetic energy of the total motion into that of the mean flow plus that of the turbulent flow ($\overline{u^2} = \overline{u}^2 + \overline{u'^2}$) requires that

a) $\overline{u}$ be regarded as a continuous function of the time, and

b) $\overline{\overline{u}\, u'}$ be zero.

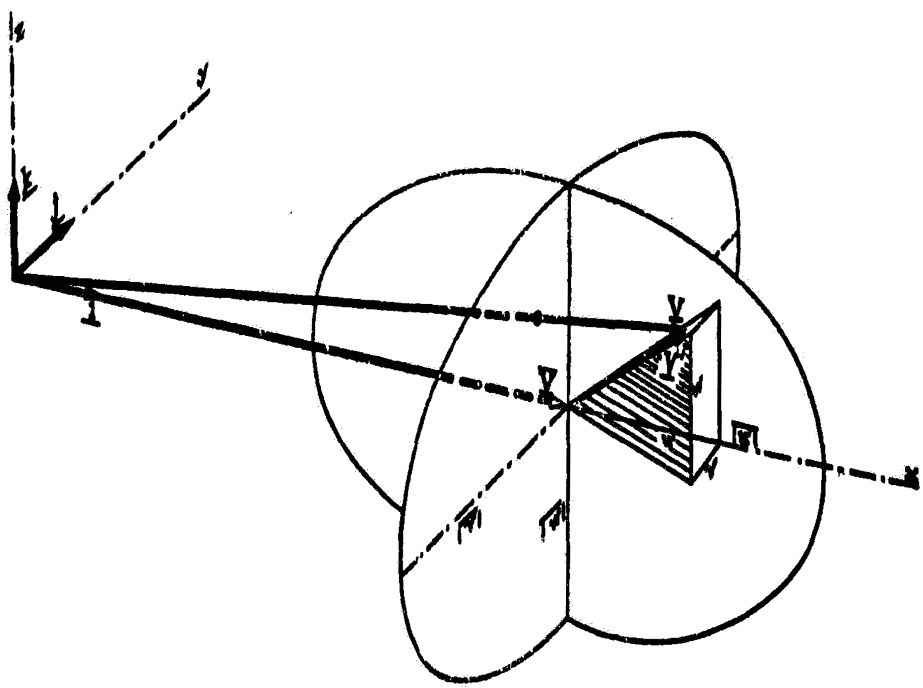
These conditions can hardly be found in the atmosphere. They would be approximately valid if the fluctuations of the wind around the mean value were sufficiently numerous within the time interval T, but owing to the lack of any break in the spectrum of eddies, a T cannot be found which is sufficiently long for every eddy size.

In order to describe the characteristics of the eddy motion, the concept of "gustiness" is commonly introduced.

The <u>components of gustiness</u>, u_g, v_g, w_g, are defined by

$$u_g = \frac{\overline{|u'|}}{|\overline{V}|} \; ; \; v_g = \frac{\overline{|v|}}{|\overline{V}|} \; ; \; w_g = \frac{\overline{|w|}}{|\overline{V}|}$$

The following picture is, therefore, obtained:



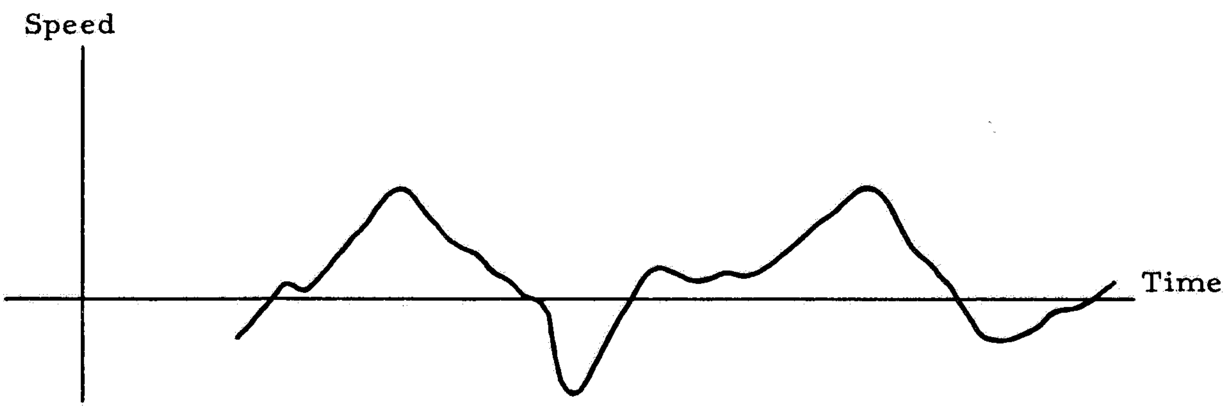
The concept of "gustiness" has been extensively applied to the study of the wind structure near the ground. A complete account of theoretical and experimental research in the field can be found in Reference 9 (Chapter 7).

From the foregoing it is evident that evaluation of eddy velocities and gustiness in the atmosphere will depend on two factors which should be decided beforehand:

a) The sensitivity of the instrument used to measure the "instantaneous" velocities;

b) The time interval selected to define the "mean" velocity.

In the definitions given above, no definition of "gust" was included. In fact, no mathematical definition of "gust" has been proposed. Strictly speaking, a gust is a "peak" in the curve of the wind speed versus time, or wind direction versus time. The difficulty lies in the criterion to be used in counting the number of peaks in any such diagram. In the example given below, the number of positive peaks could be anything from 2 to 5, depending on the time interval chosen and the speed variation considered to be significant.



Benthem (Reference 1) has analyzed the problems connected with the "counting of peaks" in a recording of the variation with time of a random variable V. He distinguishes between "peaks of the first kind" and "peaks of the second kind". The latter are defined as the greatest positive maximum or the smallest negative minimum between two zero-values of V. Peaks of the first kind are defined, on the other hand, by the set of conditions:

$$V > 0, \quad \frac{dV}{dt} = 0, \quad \frac{d^2V}{dt^2} < 0, \qquad \text{(above the } V = 0 \text{ line)}$$

$$V < 0, \quad \frac{dV}{dt} = 0, \quad \frac{d^2V}{dt^2} > 0, \qquad \text{(below the } V = 0 \text{ line)}$$

In the example given above there are, therefore, four peaks of the second kind and seven peaks of the first kind. The paper referred to above indicates discrepancies in the literature on the subject, which are due to differences in the manner of counting peaks.

The definition of "turbulent air" is closely connected with the definition of "peaks". A definition of "continuous rough air" proposed by Donely is commented upon by Benthem in the following way (Reference 1):

> "It is plausible, that the definition also holds for 'rough air' and 'turbulent air'. According to this definition an air condition is said to be turbulent if a sequence of large effective gust velocity peaks succeed each other in less than 2.2 sec. A large peak is a peak with a velocity greater than 5-8 ft/sec., which is a rather vague limit. Moreover, the boundary between turbulent and non-turbulent air becomes dependent on the flight speed and on the type of aeroplane (for, according to the N.A.C.A., the peak distance is proportional to the mean geometric chord). The statement: the peaks succeed each other in less than 2.2 sec., has to be interpreted to mean that in a fixed time-interval (some seconds ?, some minutes ? The duration of the time-interval may be very important) the average time between the occurrence of two peaks of the second kind has to be less than 2.2 sec."

It is therefore evident that it will be necessary to arrive at a certain compromise decision about the amount of detail which is desirable regarding the spectrum of eddy velocity, before a definition of "gust" can be formulated. This decision would be guided by operational experience and/or by theoretical considerations, according to the purpose which the definition has to serve. Two distinct characteristics of aircraft, which are affected by turbulence, should be considered in this regard:

a) the structural strength, which must be sufficient to cope with loads caused by gustiness; this includes both severe loads that occur very rarely and may determine the ultimate strength of the structure, and frequently repeated loads of smaller magnitude that may determine its fatigue life;

b) the controllability, which must be adequate to cope with the effect of gustiness on control, particularly in operations close to the ground.

Not only do these two considerations differ in the amount of detail with which the structure of turbulence must be known but in general they are concerned with different layers of the atmosphere. Whereas for structural strength requirements the wind-structure near the ground does not seem to present any particular problem, the surface layer is the principal one to be taken into account from the point of view of the controllability of the aircraft. In view of this fact it appears that two different definitions of "gust" might be desirable.

6. - Conclusions

The range of eddy sizes that are significant for the operation of aircraft flying in a turbulent atmosphere confines the problems connected with the structure of turbulence to a rather restricted domain. Knowledge of the response of an aircraft to turbulence is essential in order that it may be possible to define properly the parameters necessary to describe that part of the eddy motion which is of significance to aircraft.

Modern theoretical developments have advanced considerably the physical interpretation of turbulent motion. The "similarity hypotheses" allow the derivation of simple laws governing the energy transfer processes and structure of eddies. Predictions based on these laws have found experimental support in atmospheric measurements and appear to indicate that, within the ranges of importance to aviation, atmospheric turbulence is locally isotropic.

A rational classification of turbulence experienced by aircraft should take into account the statistical properties of locally isotropic eddies. Such a classification, if practicable, would serve operational needs and would provide the required material for research purposes. It is doubtful if such a result could be obtained without recording instruments.

Terminology commonly used in turbulence requires some consideration in order to remove inconsistencies and ambiguities. In particular, it appears necessary to standardize the use of expressions like "gust", "eddy velocities" and "gustiness".

Consideration of the problem connected with a definition of "gust" seems to single out the following points:

a) There appear to be two aviation requirements for definitions of gusts: one related to aircraft structural strength considerations, the other to the control of aircraft, particularly near the ground.

b) For aircraft control purposes, the layer of the atmosphere near the ground is of primary importance, whereas for structural strength purposes the gust structure in free air up to all operating altitudes should be known.

c) The WMO Resolution referred to in paragraph I, above, calls for a definition related only to conditions near the ground (anemometric level).

d) In spite of c) above, and in view of the lack of any agreed criteria for the definition of gusts at higher levels, a comprehensive analysis of the problem would be desirable in order to keep consistency in the terminology and to clarify the texts of ICAO documents which contain references to the concept of "gust" (<u>see</u> Appendix B).

7.- Action proposed to the MET Division, fourth Session

The view was expressed to the MET Division that, if the objectives envisaged in this paper were to be attained, it would be necessary:

a) to revise the classification of turbulence devised by the first Air Navigation Conference, so as to obtain a reporting scale which would be operationally practicable and at the same time would provide adequate information on the characteristics of the turbulence experienced by aircraft;

b) to review the various concepts leading to a definition of "gustiness", so as to bring consistency and precision into the terminology;

c) to formulate a definition, or a set of definitions, of "gust" which takes into account operational and design requirements.

However, since the subjects referred to under a) and c) above did not seem to be mature enough to allow of a satisfactory solution, it was suggested that, in dealing with them, the MET Division might find it necessary to confine itself to a study of the advances made in these fields and to laying down a program of work to be carried out by States and designed to lead eventually to a solution of these two problems.

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APPENDIX A TO PART II

Recommendations/resolutions of the WMO/IMO relating to definition of "gust"

1. Recommendation No. 25 of the first Session of the Commission for Instruments and Methods of Observation, WMO, Toronto, 1953

REC. 25 (CIMO-I)* - DEFINITION OF A GUST.

The COMMISSION FOR INSTRUMENTS AND METHODS OF OBSERVATION,

NOTING that the only definition of a "gust" to be found in the publication of the World Meteorological Organization is that of a "gust deemed to be of importance to aviation"; and

CONSIDERING

a) That the definition given in Resolution 131 (CD Washington, 1947) was formulated without consultation with the Commission for Aeronautical Meteorology or other aviation experts;

b) That gusts of importance to other users also ought to be specified;

RECOMMENDS that the International Civil Aviation Organization, the Commission for Synoptic Meteorology, the Commission for Aeronautical Meteorology, the Commission for Maritime Meteorology and the Commission for Climatology be invited to furnish to the Commission for Instruments and Methods of Observation a definition of a gust of importance to them, in order that the Commission for Instruments and Methods of Observation may consider what are the most desirable performance characteristics of anemometers.

* At its fourth Session, the Executive Committee of WMO, by Res. 46 (EC-IV), decided to refer Rec. 25 (CIMO-I) to ICAO, the Commission for Synoptic Meteorology, the Commission for Aeronautical Meteorology, the Commission for Maritime Meteorology and the Commission for Climatology.

2. Resolution 131 of the Conference of Directors, IMO, Washington, 1947

131 (CIMO Toronto 1947:XIII).
Wind Speed and Gusts.

The Conference recommends:

1) that a gust of importance to aviation be defined as:

"A gust is a positive deviation (departure) of the wind from the mean velocity (10 minutes mean) equal to or in excess of 10 knots (5 m/s) during at least one second but not more than 20 seconds";

2) that anemometers and wind vanes having a lag coefficient of 1 sec., i.e., in one second the instrument will indicate at least 63% of the actual wind change (90% in 1.5 sec.), are satisfactory for measuring gustiness.

APPENDIX B TO PART II

References to the concept of "gust" in ICAO Documents

1. The "Specifications for Meteorological Services for International Air Navigation"(Doc 7144-MET/521, Second Edition, 1951) refer to gustiness in several paragraphs, in connection with reporting procedures. There is an implicit assumption that "gust" refers, in those contexts, to the IMO/WMO definition which is now under consideration. Only in one instance is there a quantitative indication which establishes criteria for reporting gustiness (Appendix 3, paragraph 6.2: Criteria for warnings of gales).

2. The International Standards and Recommended Practices for Airworthiness of Aircraft (Annex 8) include definitions of apparent atmospheric gusts that are suitable for the formulation of static aircraft gustload conditions. The pertinent paragraph 3.3.1.4.1 in Part III of Annex 8 specifies minimum values of design speeds together with specific values of maximum actual gust intensities to be associated with those speeds for altitudes up to 7,600 metres (25,000 feet). Paragraph 3.3.1.4.2 and the corresponding note refer in a general way to gust gradient distances, but do not give quantitatively the distances to be considered or the relationship which may exist between gust intensity and gust gradient distance. For conventional aircraft the effect of critical gust gradient distances can approximately be taken into account by using the simplified method specified in 3.3.1.4.4 of Part III of Annex 8. Paragraph 3.11 refers to the strength of aircraft under repeated loads; however, no details are specified as yet regarding the variability and frequency of occurrence of atmospheric gusts at various altitudes and at various locations on the earth.

The controllability and performance of an aircraft is at present not explicitly expressed in terms of clearly defined gust conditions, but take-off and landing flight tests in general are arranged so as to provide for some margin covering effects of normal turbulence.

3. The International Standards and Recommended Practices for Aerodromes (Annex 14) include, in Chapter 1 of Part III, under the subject Number and Orientation of Runways, a recommendation concerning the values of maximum permissible cross-wind component to be used in estimating the usability of runways and refer to Section 2 of Attachment B for the allowances which have to be made for gusty conditions. Section 2 of Attachment B (Aerodrome usability) indicates, among the "factors which may have to be taken into account at particular aerodromes", the "prevalence and nature of gusts" and the "prevalence and nature of turbulence". This distinction between "gusts" and "turbulence" does not seem to be appropriate from a meteorological point of view, and it is by no means clear without further explanation. Furthermore, no indication is given of critical values which could be taken as a basis of reference.

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- END -

ICAO TECHNICAL PUBLICATIONS

The following summary gives the status, and also describes in general terms the contents of the various series of technical publications issued by the International Civil Aviation Organization. It does not include specialized publications that do not fall specifically within one of the series, such as the ICAO Aeronautical Chart Catalogue *or the* Meteorological Tables for International Air Navigation.

INTERNATIONAL STANDARDS AND RECOMMENDED PRACTICES are adopted by the Council in accordance with Articles 54, 37 and 90 of the Convention on International Civil Aviation and are designated, for convenience, as Annexes to the Convention. The uniform application by Contracting States of the specifications comprised in the International Standards is recognized as necessary for the safety or regularity of international air navigation while the uniform application of the specifications in the Recommended Practices is regarded as desirable in the interest of safety, regularity or efficiency of international air navigation. Knowledge of any differences between the national regulations or practices of a State and those established by an International Standard is essential to the safety or regularity of international air navigation. In the event of non-compliance with an International Standard, a State has, in fact, an obligation, under Article 38 of the Convention, to notify the Council of any differences. Knowledge of differences from Recommended Practices may also be important for the safety of air navigation and, although the Convention does not impose any obligation with regard thereto, the Council has invited Contracting States to notify such differences in addition to those relating to International Standards.

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