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# Atmospheric Gusts - A Review of the Results of some Recent R.A.E. Research

*by*

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# ATMOSPHERIC GUSTS - A REVIEW OF THE RESULTS OF SOME RECENT R.A.E. RESEARCH

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## SUMMARY

Recent R.A.E. research on gusts has been particularly concerned with severe gusts and the situations in which they occur. In the stratosphere, mountain wave conditions and those in the vicinity of thunderstorm tops have been investigated. At lower altitudes, gusts in and near thunderstorms have also been studied, as have wind and gust effects likely to be significant during take-off and landing. This work has relevance both to aircraft operations and to aircraft design. In the latter connection, recent work on mathematical models of severe gusts is also described. Mention is made of the effects of pilot control activity during flight through gusts.

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* Replaces R.A.E. Technical Report 68244 - A.R.C. 31113.

CONTENTS

## 1 INTRODUCTION

This Report gives a brief account of what R.A.E. has learned from research on atmospheric gusts since Zbrozek's review[1] of 1964. The period from that time to the present has seen[2] the consolidation of several trends which were then apparent. In particular, concern about design cases which are not primarily structural but affect handling qualities and flight control systems has increased and greater emphasis has been placed on operational aspects. (That these are interconnected is apparent from consideration of a number of accidents and incidents which became known as the 'jet upsets'[3].) In considering the usefulness of gust research, it should be noted that results which improve the ability to predict and avoid severe gusts can be applied now to current aircraft, whereas improvements in design criteria will benefit relatively few aeroplanes even in 5 years time. The basic aim of recent R.A.E. research in this field has therefore been the study of severe gusts and the situations in which they occur. This work has been done in close collaboration with the Meteorological Office (whose work is described in detail in Ref.4) and a number of overseas organisations.

## 2 SOURCES OF SEVERE GUSTS

A survey of catastrophic accidents to civil transport aircraft in which encounters with gusts played a significant part (based mainly on ICAO accident digests and taken from Ref.5 - see Appendix) shows 20 such accidents since 1950. Of these 20, 17 are clearly linked with thunderstorms, as probably are 2 others. The remaining one is the accident to a Boeing 707 near Mount Fuji[6], where structural failure occurred due to an encounter with a severe gust on the lee side of the mountain in conditions where strong mountain waves existed.

A further source of data on operational encounters with severe gusts has been the Civil Aircraft Airworthiness Data Recording Programme[7], Fig.1 shows the aircraft positions on all occasions during the first 6.8 million nm of the programme, on which normal acceleration increments exceeding 0.6 g occurred in flight. All were associated with gusts. The average number of days on which thunderstorms occur in various parts of the world[8] is also shown in Fig.1. 35% of the cases were noted by the crew as being associated with storms and a further 17% were probably so, 12% were noted by the crew as associated with jet streams, leaving 36% 'unknown'. Many of the latter, however, occurred in areas of the world at times of the year when thunderstorms are common. Of the encounters in relatively storm free parts of the world, about half of those over Italy, the U.K., and the eastern seaboard of the U.S.A., were due to thunderstorms. Taking the encounters as a whole, 54% occurred during climb or descent and 46% during cruise. The duration of the turbulence patches in which the encounters took place tended to be short (Fig.2), as noted also in Ref.9, which covers a somewhat different sample of data. The duration of half of the encounters was less than 1 minute.

A significant number of injuries (and occasionally deaths) occur to passengers and cabin crew during flight through turbulence, in almost all cases the unfortunate person not having been securely strapped into his seat. Reliable statistics are difficult to obtain but it appears that many incidents are connected with storm encounters and some with gusts associated with mountain wave systems. Very few seem to be associated with clear air turbulence (CAT) in the usual sense of the term.

## 3 GUSTS IN THE STRATOSPHERE

Operational experience at the altitudes at which SSTs will cruise is very slender. Much of the R.A.E. gust research effort in recent years has been spent in exploring this environment, which is essentially the lower stratosphere, particularly in situations in which it is thought that severe disturbances might occur. The results of this work to date, together with those of the U.S.A.F. Hicat programme[10,11], have recently been reviewed[12].

Gusts large enough for their avoidance to be desirable by civil aircraft have been found, in the R.A.E. work, in clear air near the tops of thunderstorms (up to 20 miles laterally and 10000 ft vertically from the top of the cloud), and in association with mountain waves. One patch of severe turbulence of the latter type, found at 46000 ft, contained a horizontal gust which reduced the indicated airspeed of the aircraft by 50 knots in 1 second, a similar gust of opposite sign occurring some 20 seconds later. Large and rapid changes in air temperature have been found (Fig.3) in both mountain wave (Fig.4) and storm situations. Patches of marked turbulence, particularly those associated with storms, are sometimes very short (Fig.5).

The penetration of the parts of thunderstorm clouds which penetrate into the stratosphere is likely to be at least as dangerous as thunderstorm penetration at lower altitudes, not only due to gusts but also to encounters with large hail, high concentrations of liquid water and to possible engine malfunctions due to the intensely cold temperatures which may well exist in the storm tops[13,14] (Fig.6). There is some evidence that significant gusts exist, at around storm top level[15], at rather greater distances from the storms than is the case at altitudes between 25000 ft and 35000 ft [16]. The strength of the wind, around and above tropopause level, appears to be the controlling factor in determining their strength, lateral extent and the height range affected, but present data are insufficient for firm numbers to be assigned to these relationships. However, it is clear that many thunderstorms, at least in temperate latitudes, will produce no noticeable disturbances at SST cruise altitudes. Provided that the weather radar is used correctly (particularly with reference to antenna tilt) and currently recommended practices[17,18] followed, it appears that thunderstorms will be rather less of a hazard to an SST during cruising flight than they are to subsonic aircraft.

It has been known for some time[19] that, under favourable conditions, mountain and lee waves can propagate into the stratosphere and sometimes even amplify there. During a number of flights in the stratosphere made by R.A.E.[20] over the western U.S.A., together with a Canadian N.A.E. aircraft which flew at around tropopause level, on several days significant disturbances associated with mountain and lee waves were found in the stratosphere when none was apparent around the tropopause. Estimated streamlines for the waveflow on one such day are shown in Fig.7. The occasions when significant wave disturbances were found in the stratosphere were associated with the existence of mountain and lee waves in the troposphere together with stable layers (at around the altitude of the disturbances) in the stratosphere (Fig.8). An analysis of meteorological data corresponding to the most severe gusts reported in the stratosphere in Refs.10, 21 and 22 shows similar stable layers.

Little is known, from a climatological point of view, about the existence of these stable layers but it appears that they are uncommon. Their identification with severe wave disturbances in the stratosphere is by no means certain and complete, nor do we know how far they are likely to lead to significant disturbances in the absence of a wave system in the troposphere. Further flight measurements are needed, together with a greater insight into the physical mechanisms involved. It is hoped that basic research on flow in stratified fluids will assist in this process.

At the present time, the more enlightened airlines avoid flight through areas in which significant mountain wave activity is forecast in the troposphere (e.g. Ref.23 and 24). In all known cases of encounters in the stratosphere with a significant disturbance associated with mountain waves, such a forecast would have been made, on the basis of current techniques. It therefore seems reasonable to conclude that, by planned avoidance of affected areas, mountain waves and their associated disturbances are unlikely to be a greater operational problem to an SST than they are to current aircraft*.

While the possibility exists that severe disturbances can occur in the stratosphere in other than thunderstorm and mountain wave situations, no reliable reports of them are known and it seems reasonable to conclude that at least they are comparatively much more rare. It appears, largely from the results of the U.S.A.F. Hicat programme, that gusts in the stratosphere are on the whole less frequent than at lower altitudes and when they do occur tend to be less severe. Nevertheless, these results show that in some parts of the world at certain times of the year an SST may occasionally spend 10-15% of its cruise time in turbulence of at least sufficient intensity to be noticeable to the passengers.

## 4 GUSTS AT ALTITUDES USED BY PRESENT TRANSPORT AIRCRAFT

The predominant part played by thunderstorms in turbulence accidents and incidents involving current transport aircraft has been described in section 2. This has been reflected in R.A.E. studies of gusts in and around thunderstorms at currently used altitudes and of the use of weather radar to avoid them. Much of this work has been done in collaboration with the U.S. National Severe Storms Laboratory. Gust measurements in thunderstorms had been made in a number of test series in the U.K. and U.S.A., but with the exception of some NASA measurements made in the early 1960's, no true gust velocity measurements were available. In only a very few cases could the data be compared with quantitative radar measurements of the storms.

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* This comment, and a similar one about thunderstorms, assume that SSTs will not be much different to current aircraft in the way in which they respond to atmospheric disturbances. This assumption is reasonable for the types of SST which we have so far considered.

The R.A.E.-N.S.S.L. work has allowed the relationship between gust intensity and properties of the radar echoes of the storms to be firmly established[16] over an altitude range from 23000 ft to 35000 ft. A clear relationship exists between the probability that the largest derived gust velocity encountered on a given storm penetration will exceed a given value and the maximum radar reflectivity of the storm penetrated, see Fig.9. Measurements made in convective clouds in the U.K.[25], in which derived and true gust velocity* statistics were compared and found to be in good agreement (Fig.10) suggest that results similar to those of Fig.9 apply also to the true gust velocities. Gust intensity was found to be unrelated to other properties of the radar echoes such as average reflectivity or maximum or average reflectivity gradient. For storms of a given intensity as measured by radar, a higher probability of encountering a large value of derived gust velocity was found on those penetrations which passed through the most reflective part of the storm (i.e. its core) than for those which, while still passing through a part of the storm giving an echo on the ground radar used in the tests, missed the core by more than 5 miles (Fig.11). For those penetrations which passed through the storm cores, the design values of derived gust velocity were encountered on around 10% of occasions.

Questions of the applicability of these results to storms in other parts of the world and of their interpretation in terms of airborne weather radars are considered at length in Ref.16. Suffice it to say here of the former, that until further evidence is available it seems reasonable to consider them applicable. Airborne weather radars are not so powerful, so sensitive or so stable as the ground radar used in the tests. Although available comparisons between airborne and ground weather radars are few, amounting to Ref.26 and some unpublished R.A.E. work, they provide no reason for believing that airborne systems are significantly worse so far as the detection of the positions of storms is concerned. It should be noted that there is a period of a few minutes at the beginning of any storm's life when the visible cloud and air motion are present but there is as yet insufficient liquid water to give a radar echo.

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* True gust velocities are actual components of air motion. Derived gust gust velocities are obtained directly from measurements of incremental normal acceleration, being the size of gust of a particular shape which would have produced that acceleration (see Appendix to Ref.16).

Reference has already been made to the meteorologist's present ability to forecast regions of the troposphere likely to be affected by mountain and lee waves and associated disturbances. The latter can, of course, be severe and have been responsible for at least one catastrophic accident[6]. Although no measurements of severe gusts in tropospheric waves have yet been attempted by R.A.E., some measurements made by U.S.A.F.[27], in which an instrumented aircraft was flown immediately in the lee of a high mountain ridge in strong wind conditions have been analysed and will be referred to in section 6.

Although convective clouds and waves are the situations in which, operationally, dangerous gusts are likely to be met, and R.A.E. research has therefore concentrated on them, the much more common but less intense CAT is a significant nuisance to airlines and their passengers. The current situation regarding the forecasting of CAT has been described as follows[28]: "The present position is, therefore, that we know a great deal about the possible locations of CAT, sufficient to be able to predict general areas where the chance of encountering turbulence is greater than elsewhere. This is possible mainly by identifying the position of the jetstream and predicting its intensification or decay, and its movement ........... We are not, however, in a position to forecast with certainty where in the general areas, air motion will suddenly break down into turbulence. A great deal more research is required before we can hope to narrow down these areas and give the pilot more precise warnings of rough patches."

In recent years much effort has been spent, particularly in the U.S.A.[29,30], in attempts to develop an airborne device which will detect CAT ahead of an aircraft. On the whole, the proponents of the various techniques which have been tried appear to have become less optimistic as time has gone on. At present only one technique appears to have a worthwhile chance of success. This is infra-red radiometry which is used to detect temperature changes ahead of the aircraft, it being hoped that the temperature of the patch of CAT differs from that of the surrounding air. It is known from R.A.E. and Meteorological Office work that this is not always the case, but it is possible that the correlation may improve as the intensity of the CAT increases. If the range discrimination of radiometers can be improved, there is hope that an operationally useful instrument will result.

## 5 GUSTS IN RELATION TO TAKE-OFF AND LANDING

In recent years there has been considerable interest in the U.K. in gust problems in relation to take-off and landing[31], particularly in connection with the manual landing of large aircraft[32] and the assessment of the safety of automatic landing systems[33]. Although in the poor visibility conditions for which the latter were originally intended, gusts are likely to be small, it is necessary to build up confidence in the system by operation in clear weather and some operators wish to use these systems in all weathers, not only in poor visibility.

Large gusts are, of course, most likely to occur in strong winds and are likely to be particularly serious, where large effects arise from inhomogenieties in the local terrain. (The inhomogenieties do not have to be anywhere near so large as those referred to in Ref.34 to produce significant effects.) Since much of the existing information on gusts near the ground comes from tower measurements made on sites which are flat compared with most airfields, their applicability to take-off and landing problems is doubtful. This applies particularly to measurements of vertical gusts at heights below about 200 ft. Much more work needs to be done in conditions similar to those of practical interest before conditions can be defined with decent confidence.

From the operational point of view, both to give a needed improvement in the prediction of the severity of conditions for present day piloted aircraft[35] and to allow the placing (where necessary) of sensible limits on the conditions in which automatic landing systems may be used, it is essential that the severity of gusts likely to be met on the landing approach be related to general meteorological parameters, or their forecasting be facilitated by some other means.

The importance of windshear effects (in the sense of the variations with height of the speed and/or direction of the wind which persist for periods of a minute or more) can be much over-rated. At altitudes which are of primary concern from a landing safety viewpoint (below about 200 ft) such shears are likely to break down into turbulence which give much greater fluctuations of wind to an aircraft than would the original steady shear. Large shears are much more likely to occur above 200 ft than below, and at these altitudes the gusts primarily affect glidepath performance rather than directly affect landing safety. A system, either human or automatic, which can cope with the average level of gustiness likely in a 30-40 knot wind is not likely to be greatly troubled by windshear, except perhaps for the human pilot who is taken by surprise. However, significant shears may be associated with large temperature stratification and important wave effects may occur occasionally at a few airports.

Large and rapid fluctuations of wind are not confined to situations in which the mean wind preceding them is strong. Large gusts which occur when the wind had previously been relatively light are associated with convection around and above the earth's boundary layer and the larger of them (which have resulted in a number of accidents[31]) are associated with thunderstorms[36] and are usually referred to as squalls. The anemogram of a particularly horrendous example, taken from Ref.37, is shown in Fig.12. Squalls smaller than this, but still large enough to be troublesome, occur relatively frequently in the U.K.[36]. The average number per year at R.A.E. Bedford, over the last 5 years, has been 40. Two examples of these are given in Fig.13. A transport-type aircraft was flaring prior to a landing (on a westerly heading) when the squall of 15 November 1966 occurred. The aircraft touched down with a large sideways velocity and had the runway not been wet, allowing the aircraft to slide sideways, the results could well have been most unpleasant. The changes in wind direction in squalls can sometimes be more rapid and spectacular than the changes in windspeed, as shown in Fig.14.

Squalls do not appear to have been studied very much, from a meteorological point of view, and the account given in Ref.38 appears to be the most detailed available. Some data on rapid wind changes is given in Ref.39, but it is not clear how far this is representative of squalls as discussed above and how far it concerns wind changes associated with the passage of large-scale fronts.

A very large number of squall records, such as those shown in Figs.13 and 14, are available from the Meteorological Office but their timescale is such that the rapidity of the fluctuations cannot be resolved to anything like the accuracy needed to determine the effects they would have on aircraft. In an attempt to obtain further information, continuous records of windspeed at heights of 33 ft, 50 ft and 100 ft are being obtained on an expanded timescale using an instrumented tower at R.A.E. Bedford. No large squalls have yet occurred but a record of a relatively small one is given as Fig.15. Although the recording speed used is some 12 times that of the standard Meteorological

Office instrument, it is still inadequate to resolve the more rapid fluctuations. A further recording system, giving an additional speeding-up by a factor of 30, has therefore been introduced in the last few weeks. An interesting record of an almost step-like gust obtained with this system is shown in Fig. 16.

The coming operation of VTOL and STOL aircraft into and out of urban areas is likely to lead to demands for knowledge of the gust environment in such places. Very little useful information is available and research will be necessary in the near future.

## 6 THE DESCRIPTION OF GUSTS

### 6.1 Gust spectra

Up to the mid-1950's the 'discrete gust' approach to gust loads was practically universal. In this, gusts are considered to be of a fixed and relatively simple shape (a ramp or 1 - cosine function with a fixed length defined either in feet or aircraft chord lengths) and variable size. Although, in fact, gusts are not really like this, the approach has worked well and is still the primary one used by the aircraft industry.

'Spectral methods' were introduced to gust load studies in the late 1940's, having been used in the description of turbulence, from a fluid mechanics point of view, for the previous 20 years. The gusts are here conceived as examples from a random process with a determinate spectral density (average variation of energy with frequency or wavelength). Knowledge of this spectral density together with that of the dynamics of the aircraft (variation of response with input frequency) allows the spectral density of the response to be calculated if the system is linear. Thus rational account could be taken of the effects of aircraft rigid body and aeroelastic dynamics, which were becoming of increasing importance.

If, in a homogeneous region of stationary random air turbulence, energy is fed in only at the long wavelengths, it is a well-known result of Kolmogorov that the spectral densities of the turbulence components will decay as the five-thirds power of wavelength over a range (known as the inertial subrange) from around the shortest wavelength at which energy is being fed in, down to wavelengths of a few centimeters, where viscous effects begin to predominate[41,42]. Given the assumptions made, the five-thirds power law is a reflection of the physical properties of air. However, if the turbulence was not homogeneous - for example, if energy was being fed into it in a region where measurements were being made, but due to the mean flow the decay partly took place somewhere else - a slope steeper than five-thirds would be expected over part of the frequency range. Many examples of spectra measured in this kind of situation show a square law decay; e.g. Fig.20 [40].

As wavelength increases to values around those at which energy is being fed into the turbulence, the spectral density begins to flatten. The wavelength at which the bend occurs is a measure of the 'scale' of the turbulence. There are many definitions of this quantity, most of them defining the numerical value of the turbulence scale as effectively proportional to but not equal to this wavelength. The generally used 'theoretical' turbulence spectra due to Dryden, von Karman etc, show a fairly abrupt bend and an almost flat spectrum at long wavelengths. Such evidence as is available tends to suggest that in practice the bend is not so abrupt, as indicated in Fig.18. Many measured spectra do not show a bend at all, and measurements at the long wavelengths involved are very demanding on instrumentation accuracy. As this has improved the values of turbulence scale obtained have tended to increase, the generally recommended value having increased tenfold in the last 10 years.

Taking, rather arbitrarily, the Dryden formula and matching the appropriate autocorrelation functions* with those measured (Fig.19), turbulence scales ranging from 1750 ft to 7800 ft have been obtained from examples of the vertical component of turbulence measured in clear air near storm tops[12]. Corresponding values inside the thunderstorms range from 750 ft to 2300 ft, these being for the spectra shown in Fig.17. Some rather unexpected results have recently been obtained by R.A.E. from measurements of vertical gusts at heights between 50 ft and 200 ft over Bedford Airfield. These gave scales which tended to be greatest at the lower altitude, contrary to expectations, and the numerical value at 50 ft is much longer than was thought likely. While it is not suggested that these few results at low altitudes call for an immediate revision of ideas, more evidence is badly needed from sites of practical interest such as airfields and their approach areas.

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* The autocorrelation and spectral density are Fourier transforms of each other.

The spectral densities described above show how, on the average, the energy of the turbulence varies with wavelength. Spectral methods also provide a valuable tool for comparing measured aircraft loads and motions with theoretical predictions and provide a good insight into the accuracies which are attained in the latter[43,44,45]. This is, however, not the primary question which concerns the aircraft designer. What he usually wants to know is how often something, often a relatively extreme and rare event, will occur. The spectral density, alone, will not tell him this.

### 6.2 Gust probabilities

If gusts were a Gaussian process, knowledge of their spectrum and root mean square would, theoretically, allow any desired probability to be calculated and, if the aircraft behaved as a linear system, response probabilities could be obtained. In particular, the average frequencies at which given loads are likely to be exceeded could readily be obtained. Unfortunately, the overall probability distributions of gust loads encountered operationally are nothing like Gaussian. Rather, the large loads are usually a good approximation to an exponential distribution[46]. The usual way round the difficulties which this causes[47,48] is to assume that each individual turbulence encounter is with a Gaussian process but that the rms values corresponding to each encounter may be different.

The usual method of calculating the average frequency of zero crossings per unit time of a function from knowledge of its rms and spectrum shape[49] is only mathematically correct if the function and its first derivative are jointly Gaussian. In this situation there is good agreement between experiment and theory[50]. However, results obtained on flights through convective clouds[25] where the probability distributions for the individual cloud penetrations do not appear to have been near Gaussian, show wide variations in the zero crossing frequencies of both cg normal acceleration and true vertical gust velocity (Fig.20). The percentage of runs on which the maximum exceeds a given factor times the rms is much greater, in both the convective cloud[25] and thunderstorm[16] flights, than would obtain with a Gaussian process (Fig.21).

In relation to aircraft response, a property of the true gust velocity which can usefully be considered is the transition function, which is the change in gust velocity which occurs over a fixed time or distance ('lag'). The rms of the transition function is usually called the structure function and is uniquely related to the autocovarience, whether or not the process is

Gaussian. For a given patch of moderate or severe turbulence, the probability that transitions in excess of a given value will occur tends to be exponential for values more than about twice the rms in all the examples so far examined[51,52], and sometimes is close to exponential even for small values, as shown in Fig.22.

A rather more subjective approach to the analysis of large gusts was made in Ref.40. Here, an examination was made of time histories of true vertical gust velocity measured in thunderstorms by R.A.E., together with some reported in Ref.27, which were measured immediately in the lee of a mountain range in strong winds. Changes in gust velocity which occurred over given distances were picked out by eye. Any change exceeding the threshold used was considered to be a gust of some length and gusts of different lengths were not permitted to occur simultaneously. The probability distributions of gusts exceeding a given size were found to be exponential for each gust length and (for each source of gusts) differed from each other by a constant factor when an exponent of gust size divided by the square root of gust length, rather than of gust size itself, was used (as shown in Figs.23 and 24). Curves showing the variation with gust length of lines of equal probability of gust velocity exceedance are shown in Fig.25. In comparing the behaviour of different sizes of aircraft, it is sometimes convenient[40] to consider the behaviour of lines of equal value of the product of the number of gusts exceeding a given size and the gust length and such curves are shown in Fig.26.

It is clear from the foregoing that the assumption that atmospheric gusts, on the whole or as individual patches, are a Gaussian process, lacks physical reality. This is not to say that spectral techniques (particularly those which in effect compare the responses of two aircraft rather than make a direct appeal to data on the atmosphere) based on the Gaussian assumption may not be a useful advance, from an empirical point of view, on what has gone before. But they are not 'rational design methods' based on a physical understanding of atmospheric gusts.

A further example of the practical application of the Gaussian assumption concerns the use of synthetic turbulence made with Gaussian noise generators, the output of which is filtered to give the correct spectral density. These have frequently been used in rig testing of automatic flight control systems and in simulators. So far as the prediction of extreme values is concerned, this synthetic turbulence does not have the same properties as the atmosphere.

## 6.3 Theoretical models of gusts

The above doubts about the validity of Gaussian process representations of turbulence had led to a search for theoretical models which, while utilising spectral ideas in considering the average distribution of energy with wavelength, have probability characteristics which match those of the real atmosphere. A number of concepts are being studied, including those of the transition function mentioned earlier and of self-similar intermittent random processes and several promising ideas have emerged[53,54]. This work has been of great value in suggesting ways of looking at severe gust data and of considering such questions as the effect of turbulence scale on the probability properties of the gusts. For example, Ref.53 predicts the equal slopes of the curves on Fig.23 from the spectrum shape shown in Fig.17. Curves comparable with those of Figs.25 and 26 (although the definitions of 'gusts' are somewhat different), calculated for self-similar gusts with spectral density varying as the square of wavelength and infinite scale, are shown in Figs.27 and 28.

More experimental data on severe gusts, as well as theoretical interpretation, is needed before a physically valid model of them can be put forward for use in design. Good progress is, however, being made towards this end.

## 7 THE EFFECTS OF PILOT CONTROL ACTIONS ON FLIGHT THROUGH GUSTS

Although the research described above was done primarily to study the gusts themselves, their effects on the test aircraft and crew have also been considered.

Mention was made earlier of a series of gust accidents and incidents known as the jet upsets[3] and similar accidents[55,56] appear to have happened to propeller driven aircraft. A feature of the jet upsets was a pitching oscillation[3] with a period of about 20 seconds which tended to be divergent, the aircraft finally bunting over into a dive. A similar oscillation (Fig.29) occurred on one of the R.A.E. flights through convective cloud with a fighter aircraft, and only damped out when the pilot regained visual reference.

Comparison of the same pilots flying the same aircraft through similar turbulence in visual and in true instrument conditions reveals, as illustrated in Fig.30, greater control activity in relation to the turbulence level in the latter case, with a strong tendency for the larger accelerations to be closely related to elevator deflection. Fig.31 shows the variation of the ratio of rms derived gust velocity to rms true gust velocity with the latter quantity for a series of flights with a fighter aircraft through convective cloud. Since, in effect, the rms derived gust velocity can be taken as proportional to the rms cg normal accelerations, corrected for the effects of height, weight and speed, Fig.31 shows a tendency for pilot control actions to have a decreasingly deletereous effect on accelerations (and so on loads) as gust intensity increases. An unpublished analysis by Zbrozek of data from Ref.57 shows (Fig.32) a similar effect. However, data on the maximum acceleration experienced on each cloud penetration indicates that the effect of gust intensity on the ratio of maximum acceleration to maximum true gust velocity is less marked than on the rms (Fig.33).

Operational flight recording data also show[9] that pilot control actions can have a significant effect on the loads experienced during flight through moderate or severe gusts. At the present time there is no way of taking account of these effects. Until such is available, gust load prediction will be an inexact business, however good our knowledge of the atmosphere.

## 8 CONCLUDING REMARKS

The past few years has seen an increasing concern, on the part of those involved in aircraft operations, about the effects of atmospheric gusts and the means of avoiding particularly the more severe ones. The great concern expressed in some quarters about CAT (clear air turbulence) appears, in the light of accident and incident data, to be somewhat misplaced. The thunderstorm is still the greatest hazard, but the severe gusts which can occur in mountain wave conditions, long recognised as a hazard by some, are now widely known.

The more enlightened airlines have, in recent years, increased efforts in crew training in the use of airborne weather radar for storm avoidance. Although it might be suggested that no great improvements in the radar itself can be foreseen, improvements in the display of information to the pilot are possible. Convincing arguments can be advanced, however, to suggest that, in at least some areas, airborne radar alone is not enough, and a good weather display to the air traffic controller is also needed.

Although no great improvements in gust aspects of weather forecasting seem likely in the immediate future, considerable advances have been made in understanding of the physical mechanisms responsible for severe gusts. There are, however, still large gaps in our knowledge. The realisation that severe gusts are not just larger versions of the more common less severe ones, but may differ from them in kind as well as in degree, implies that measurements must be made of the severe gusts themselves and so increases the difficulties (and dangers) of experimental work.

The use of gust statistics (such as the spectral density) which describe averages in order to predict extreme values for design cases is, unless adequate regard is paid to other probability properties, a questionable procedure. There is now clear evidence that these properties are not Gaussian. Work on theoretical models of extreme gusts which are more physically plausible than those used in the past is showing good progress and should lead to truly rational design criteria. It has, however, been pointed out that account must be taken not only of the gusts but of the resulting control activity of the human pilot.

## Appendix

## ACCIDENTS TO CIVIL AIRCRAFT INVOLVING TURBULENCE IN WHICH MAJOR STRUCTURAL FAILURES OCCURRED IN FLIGHT

| Date and place | Aircraft | Weather |
|---|---|---|
| Jun '50 U.S.A. | DC 4 | Line squall with thunderstorms. |
| Jan '51 Natal | Dove | Dark rain cloud. |
| Sep '51 Greece | DC 3 | Scattered thunderstorms. |
| Feb '53 Mexico | DC 6 | Frontal wave with thunderstorms. |
| May '53 India | Comet 1 | Thunderstorm. |
| May '53 U.S.A. | C46F | Scattered thunderstorms, accident at squall line. |
| Jul '53 Pacific | DC 6A | Extreme thunderstorm activity. |
| Aug '57 Alps | Learstar 18 | Cold front with severe turbulence and some thunderstorm. |
| Dec '57 Argentina | DC 4 | Cold front with thunderstorms and severe turbulence. |
| Mar '59 India | DC 3 | Thunderstorm. |
| May '59 U.S.A. | Viscount | Cold front with large, rapidly developing thunderstorms. |
| Jul '59 U.S.A. | B26C | Thunderstorm. |
| May '60 Argentina | C46F | Cold front. Jet stream "brought air masses down from hills". |
| Sep '60 Elba | Viscount | Cold front with thunderstorms. |
| Jul '61 Argentina | DC 6 | Cold front with scattered thunderstorms. |
| Nov '61 Australia | Viscount | Thunderstorms. |
| Feb '63 U.S.A. | B720B | Squall line with thunderstorms. |
| Jul '63 India | Comet 4C | Monsoon thunderstorms. |
| Mar '66 Japan | B707 | In lee of Mount Fuji in wave conditions. |
| Aug '66 U.S.A. | BAC 111 | Extensive linked thunderstorms. |

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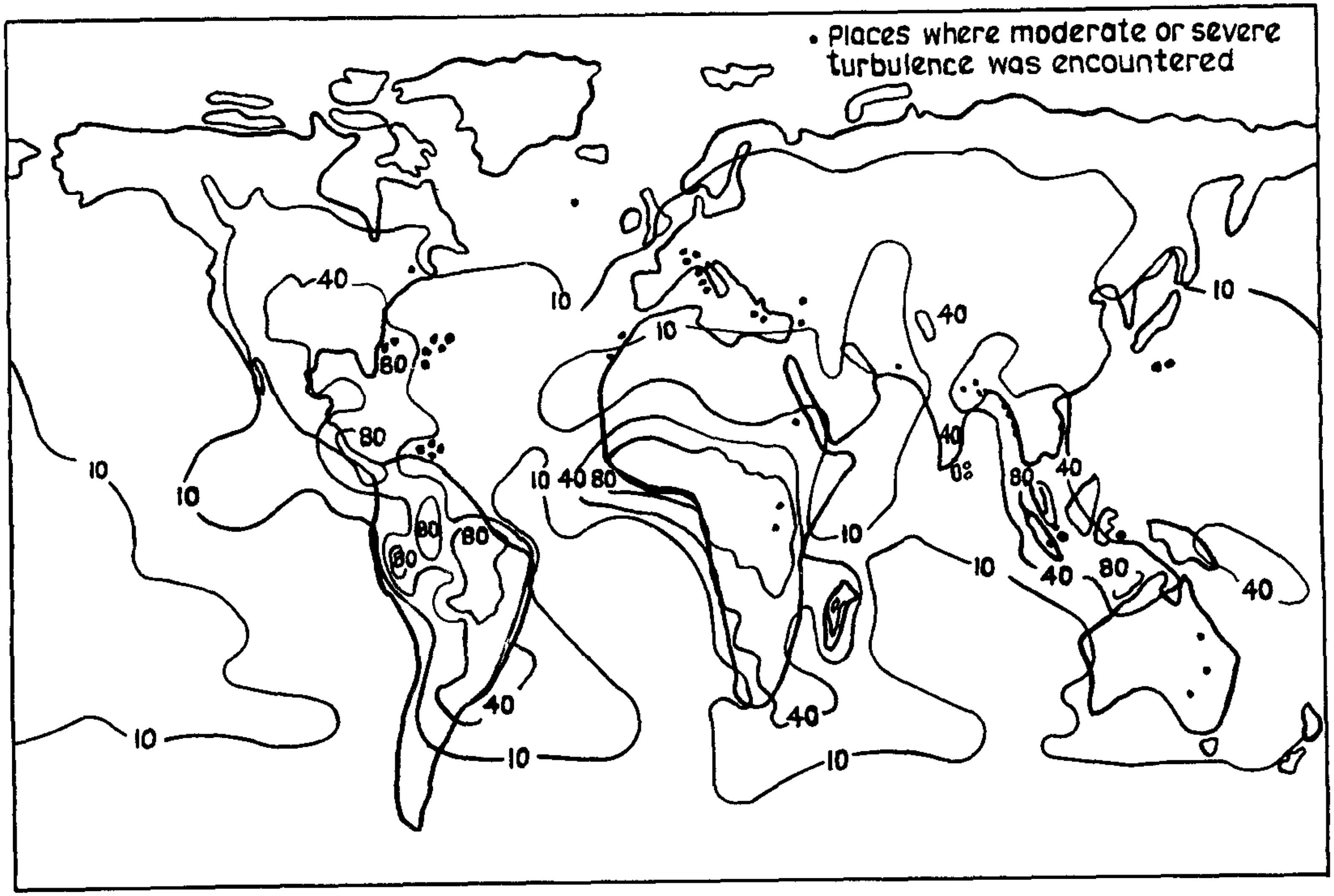


Fig.1 Positions where moderate or severe turbulence was encountered during worldwide civil aircraft operations and average numbers of days per year on which thunderstorms occur

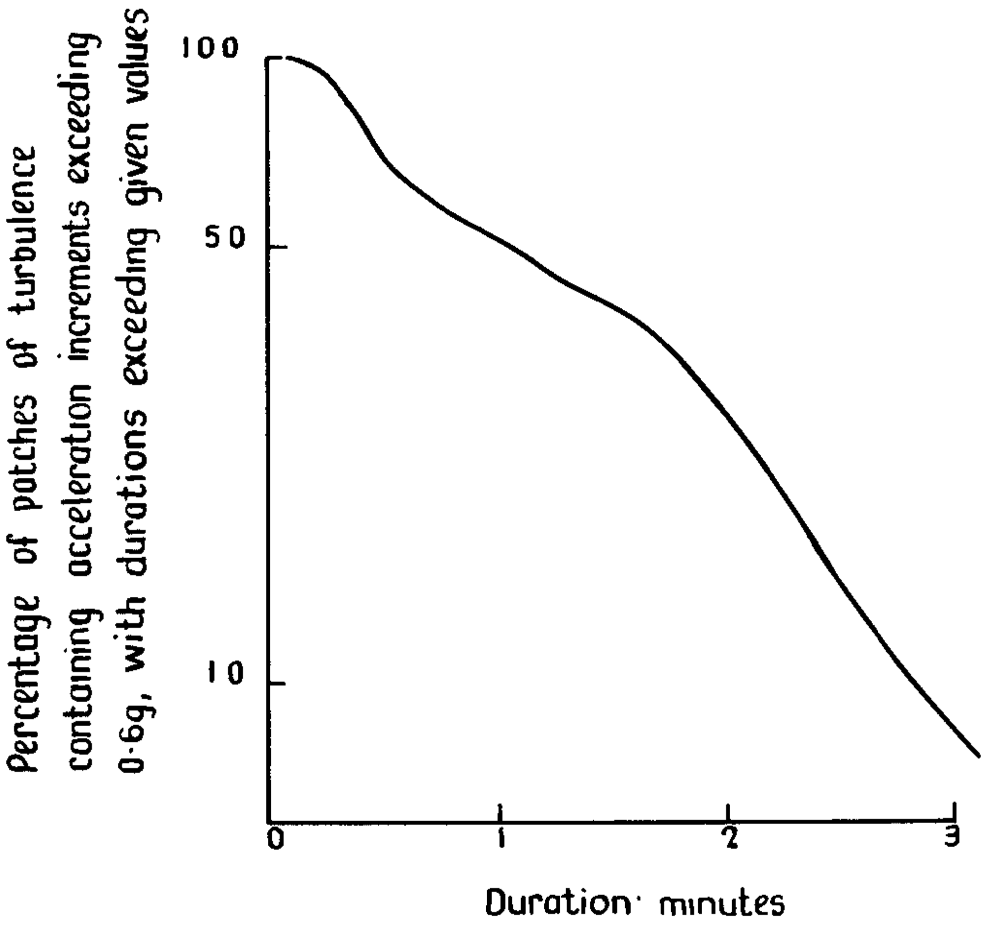


Fig. 2 Duration of patches of moderate and severe turbulence encountered on worldwide civil jet operations

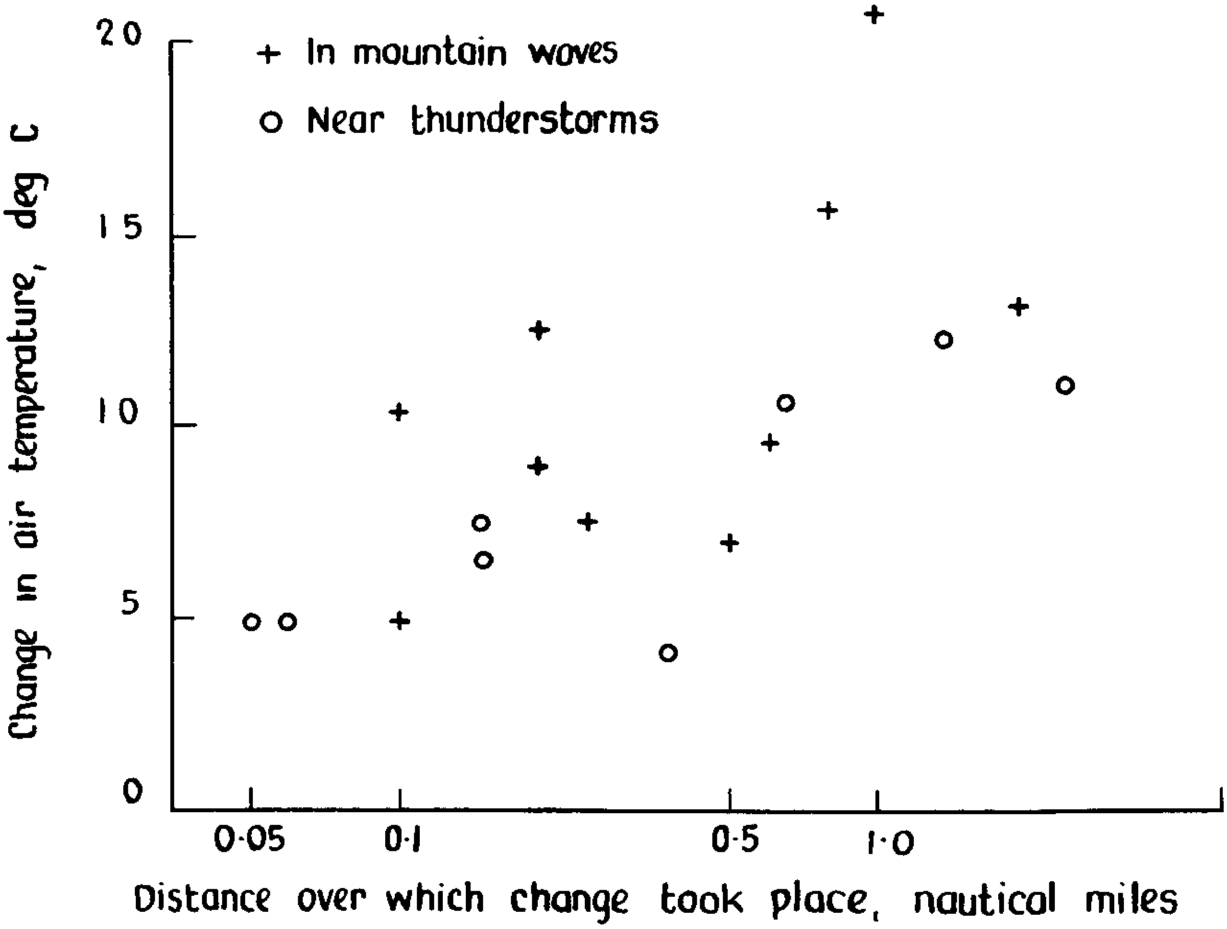


Fig. 3 Examples of large and rapid changes in air temperature encountered in the stratosphere

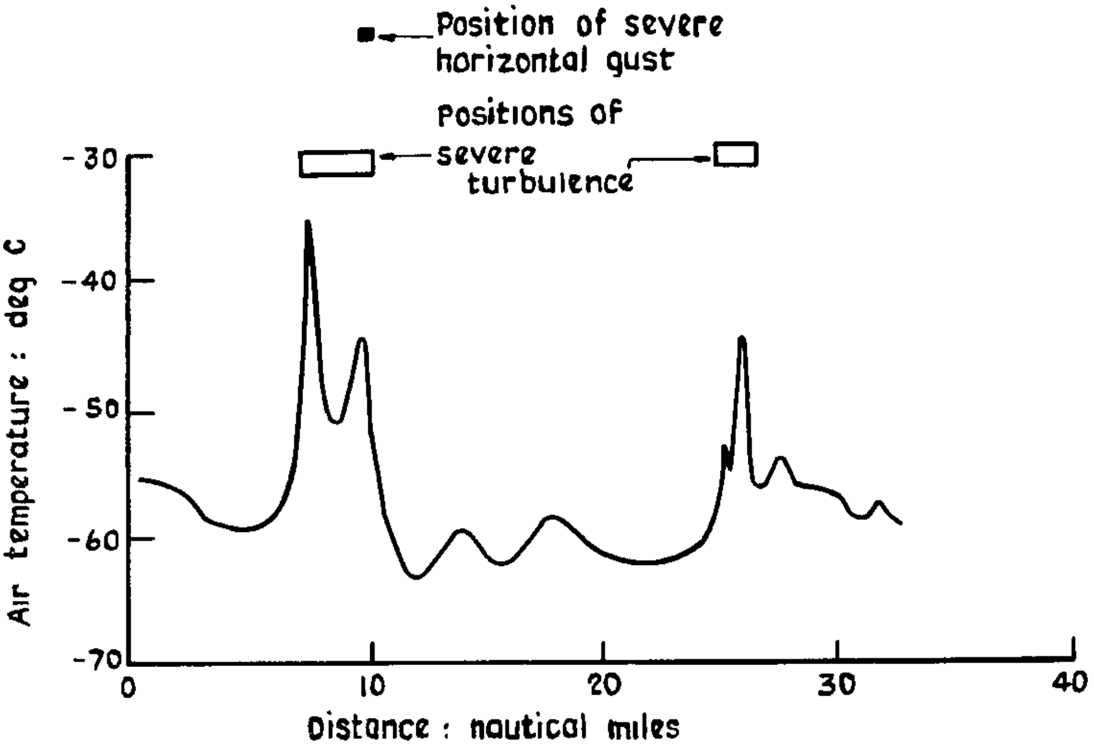


Fig. 4 Time history of air temperature encountered during flight through a mountain wave at an altitude of 46 000 ft

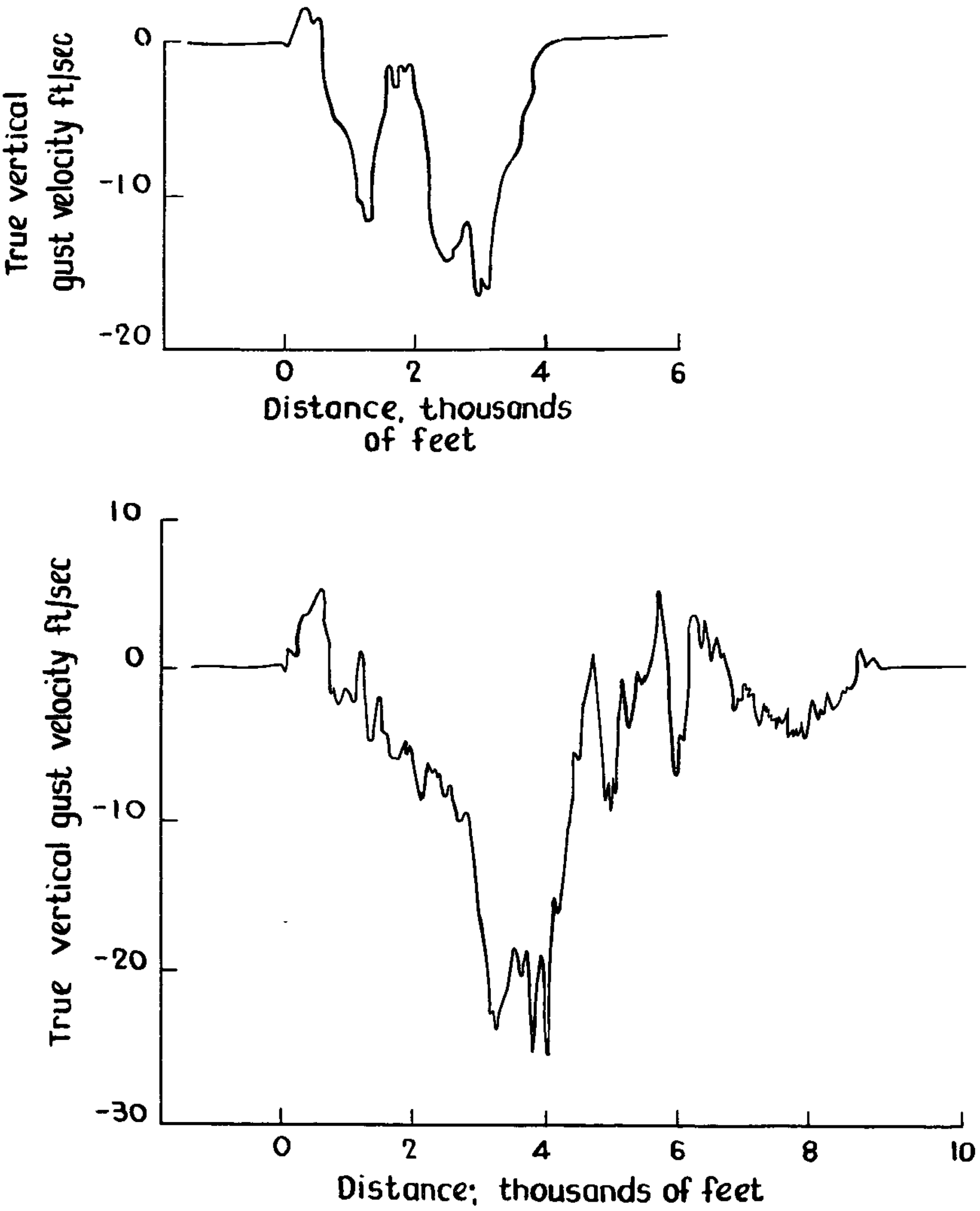


Fig.5 Examples of gusts measured in clear air near thunderstorm tops

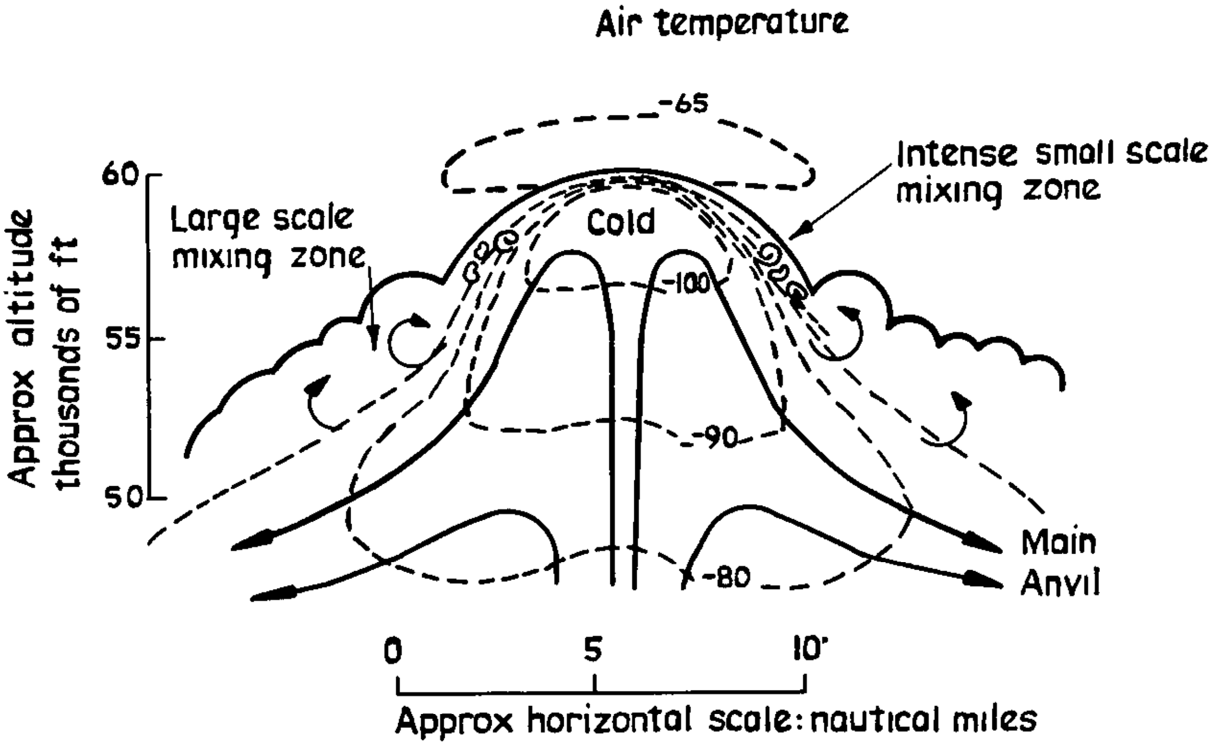


Fig 6 Tentative model of a quasi-steady storm top (from ref 14)

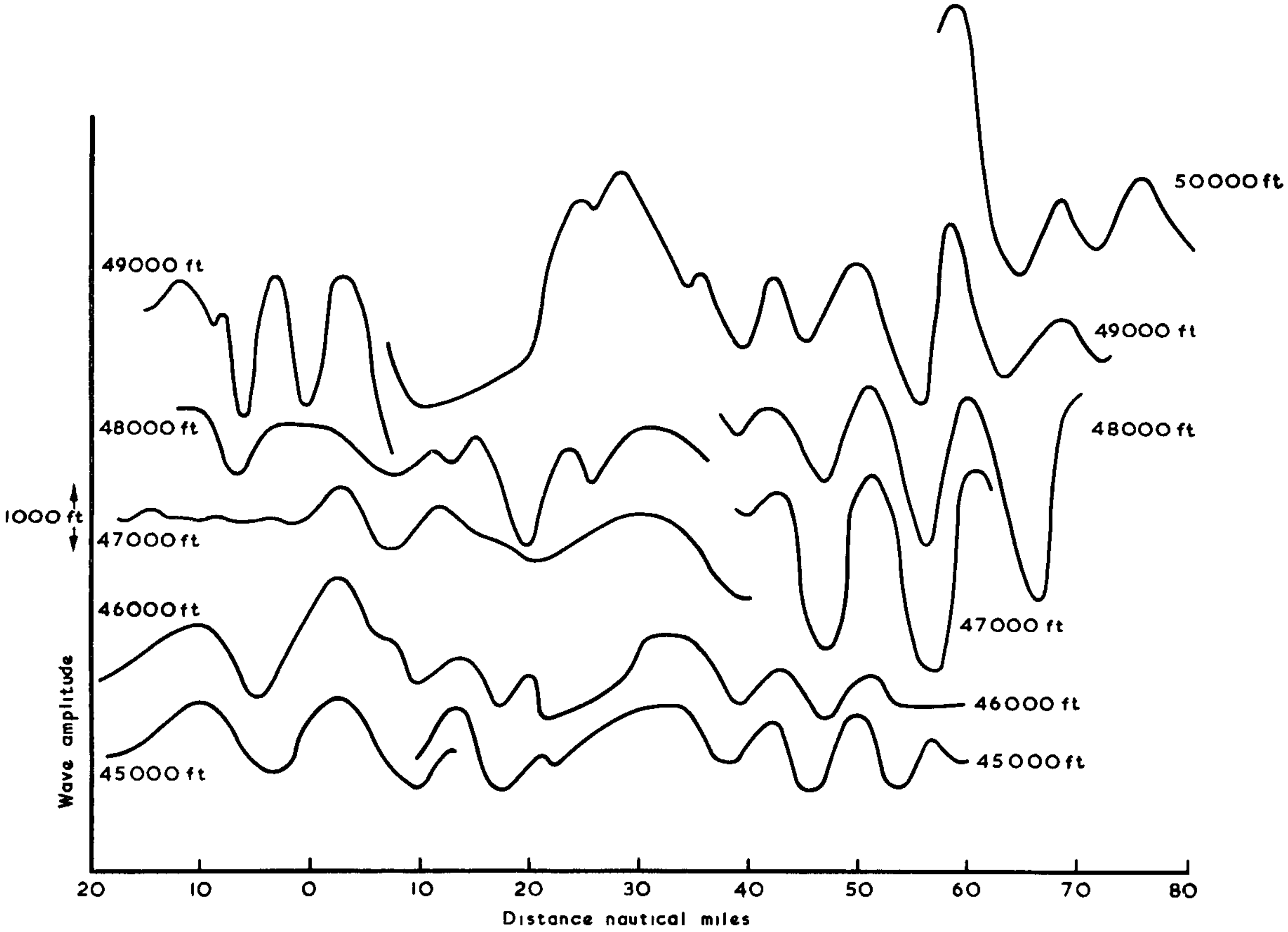


Fig. 7 Streamlines of flow in mountain waves over the western USA, based on constant potential temperature surfaces

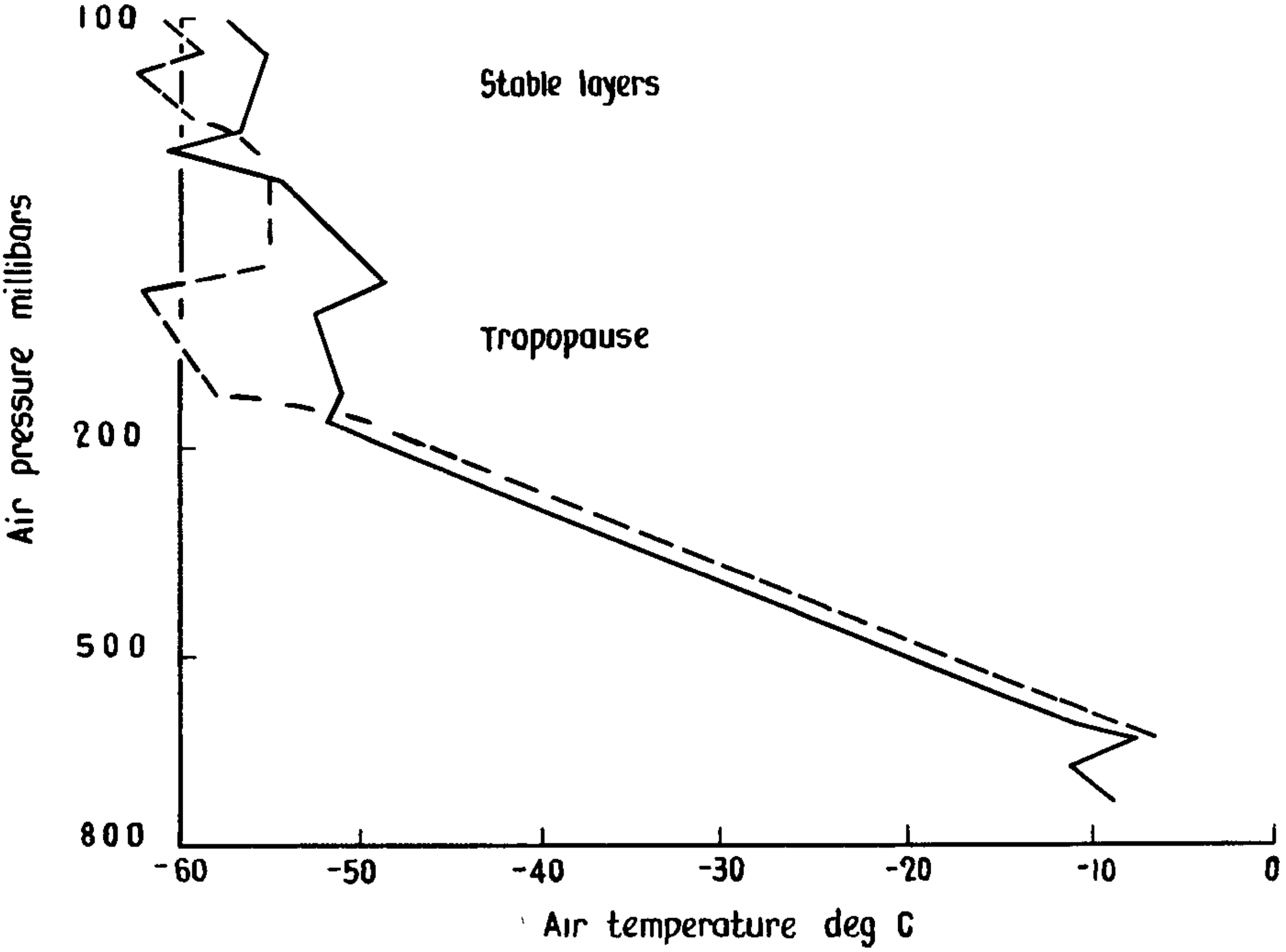
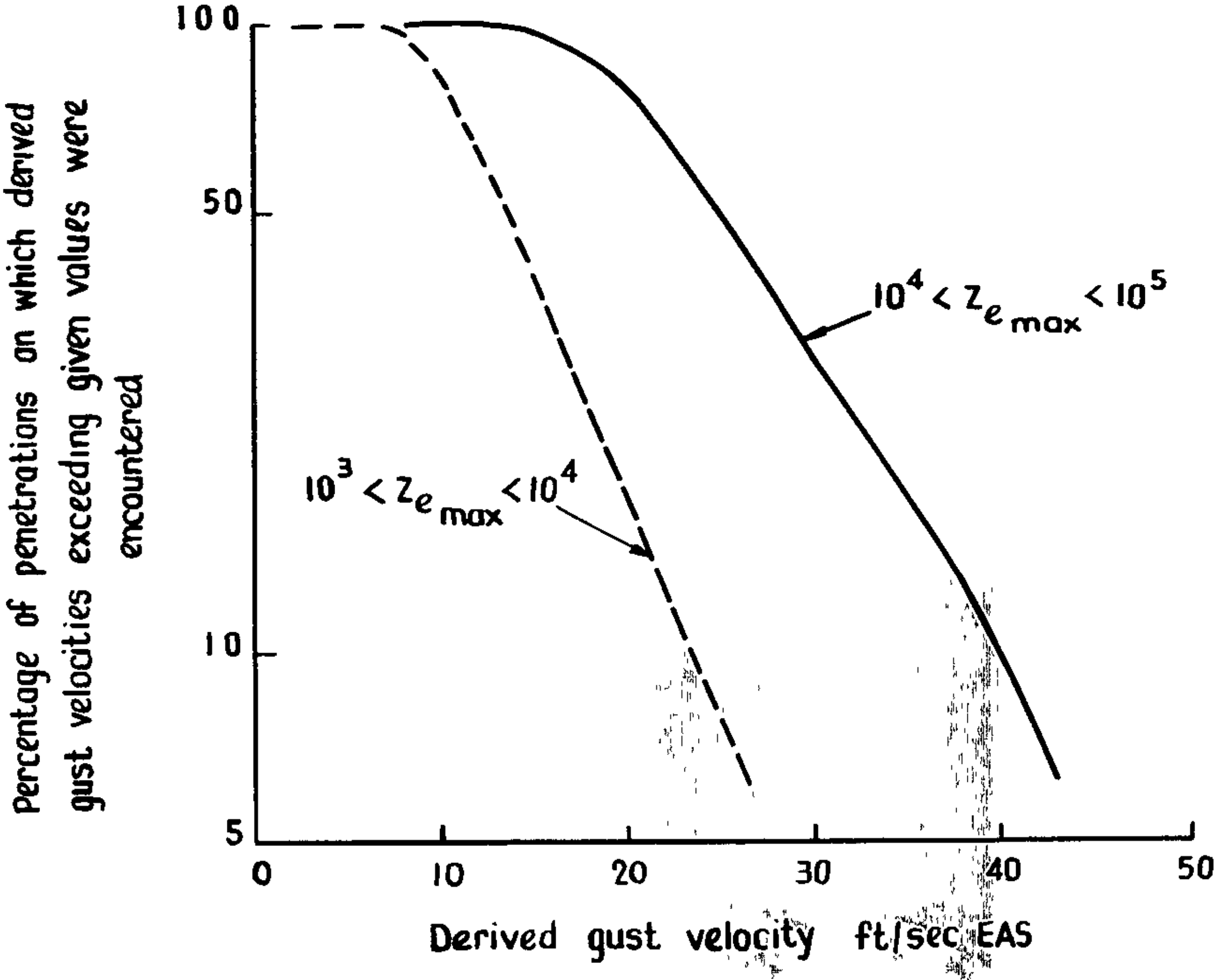


Fig. 8 Examples of upper air temperatures showing the existance of stable layers in the stratosphere



$Z_{e\,max}$ is maximum radar reflectivity of storm $mm^6/m^3$

Fig. 9 Effect of the maximum radar reflectivity of the storm on the maximum derived gust velocity encountered on thunderstorm penetrations

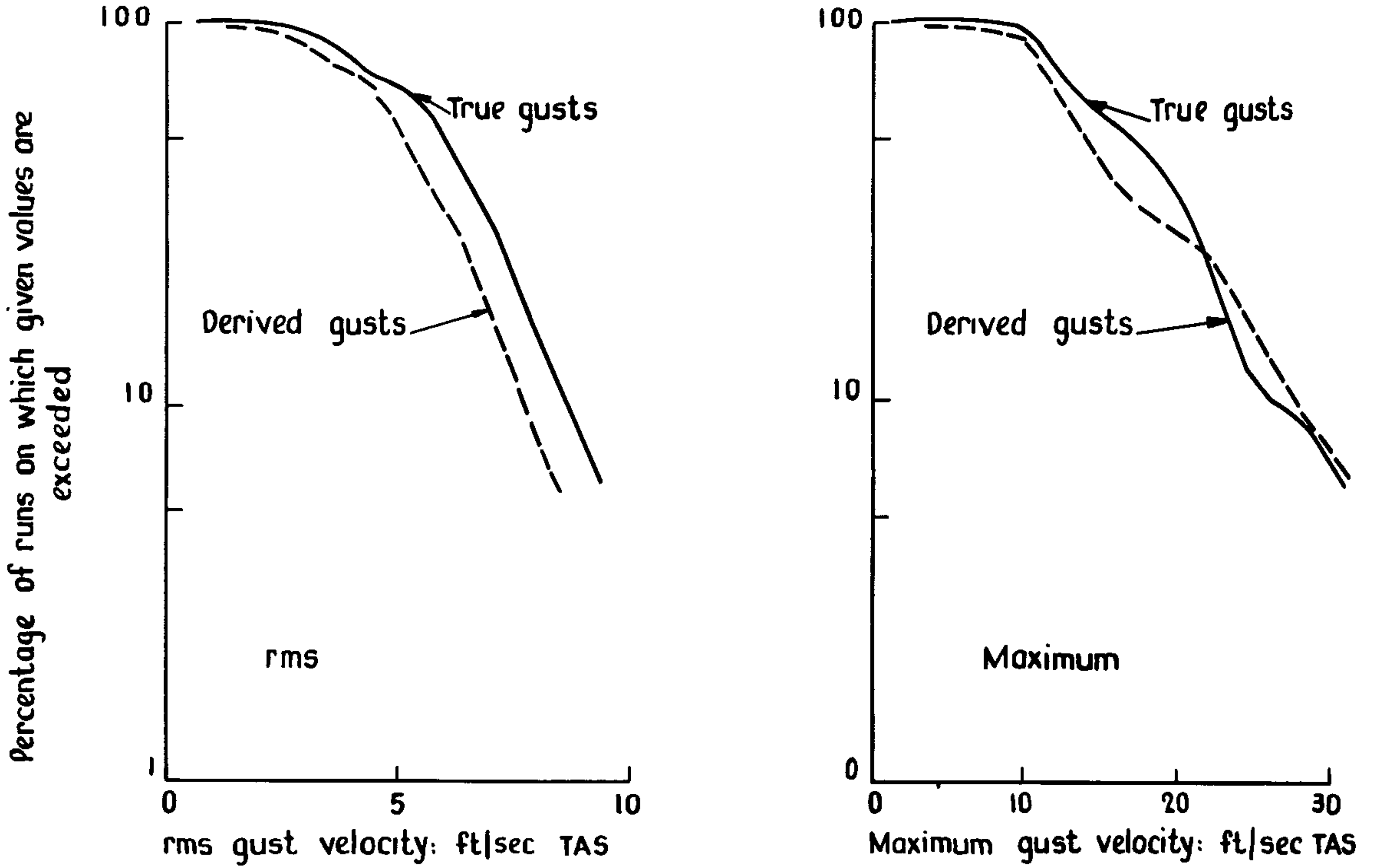


Fig.10 Probabilities of encountering given rms and maximum gust velocities from flights through convective cloud

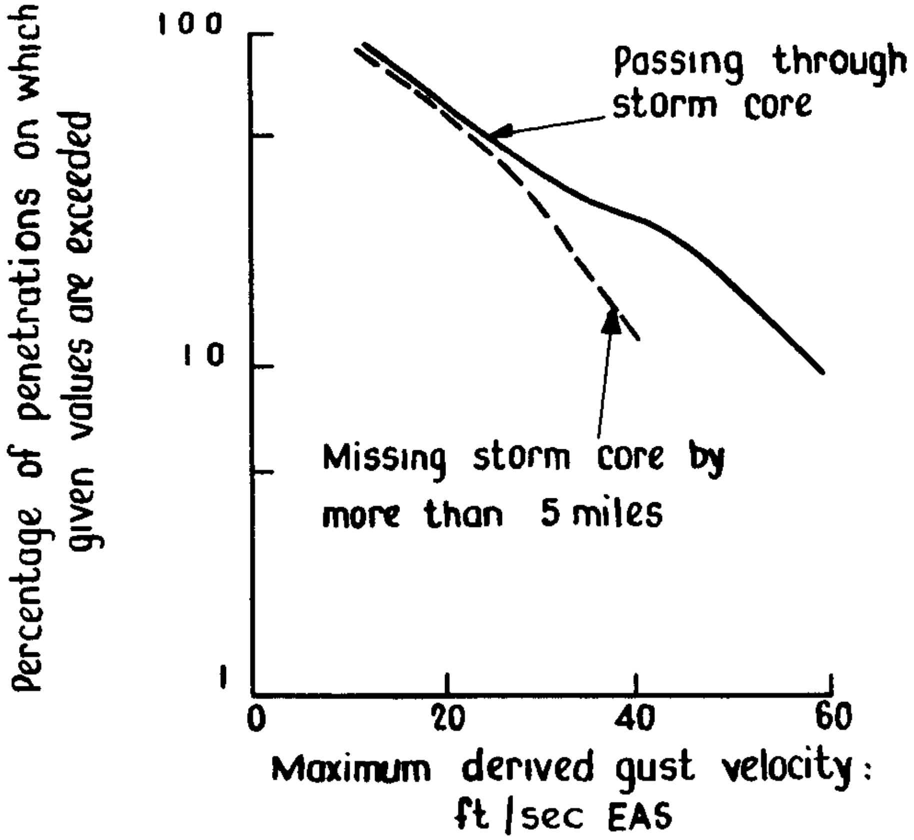


Fig. 11 Effect of passing through or missing the storm core, on maximum gust velocities encountered on thunderstorm penetrations (at heights between 23000ft and 28000ft through storms with maximum reflectivities between $10^4$ and $10^{5\cdot5}$)

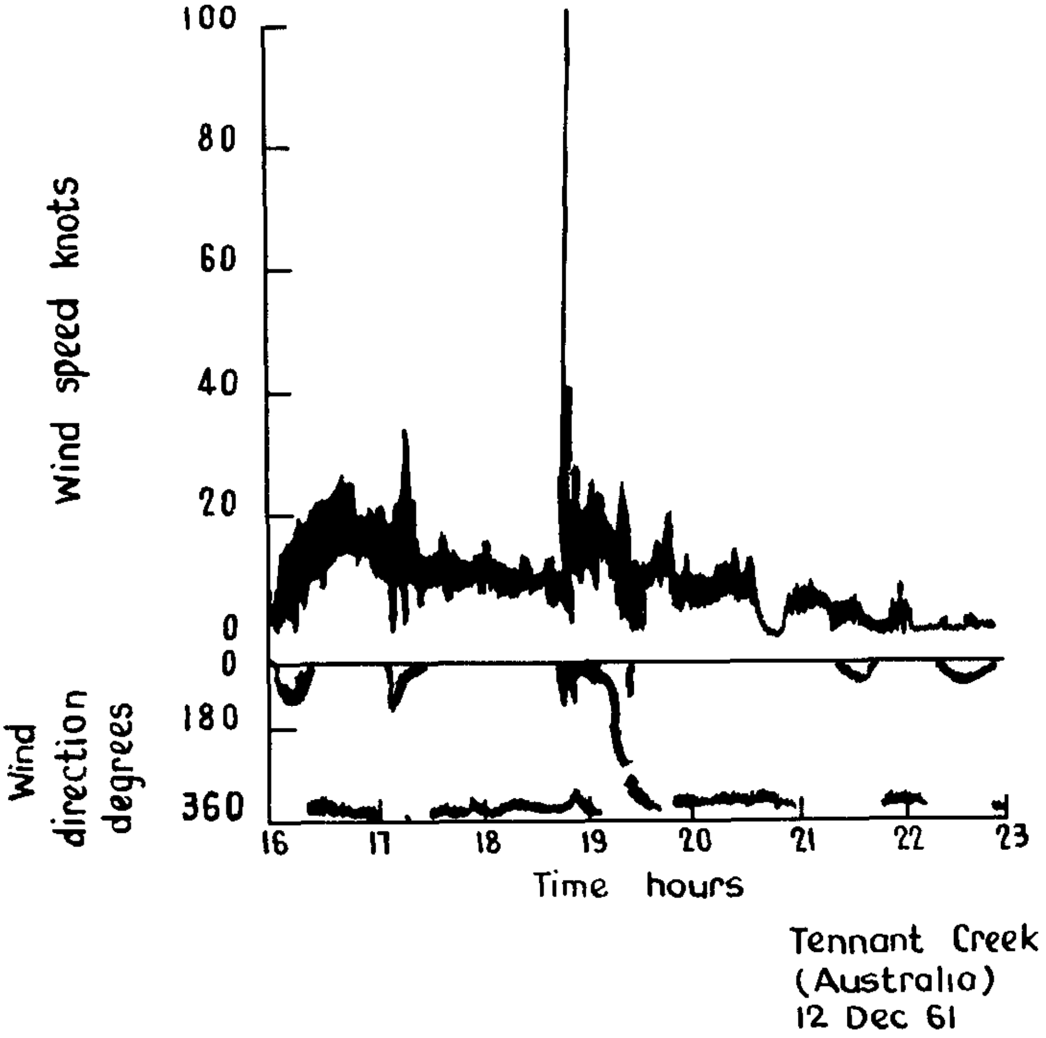


Fig. 12 Anemogram of a large squall

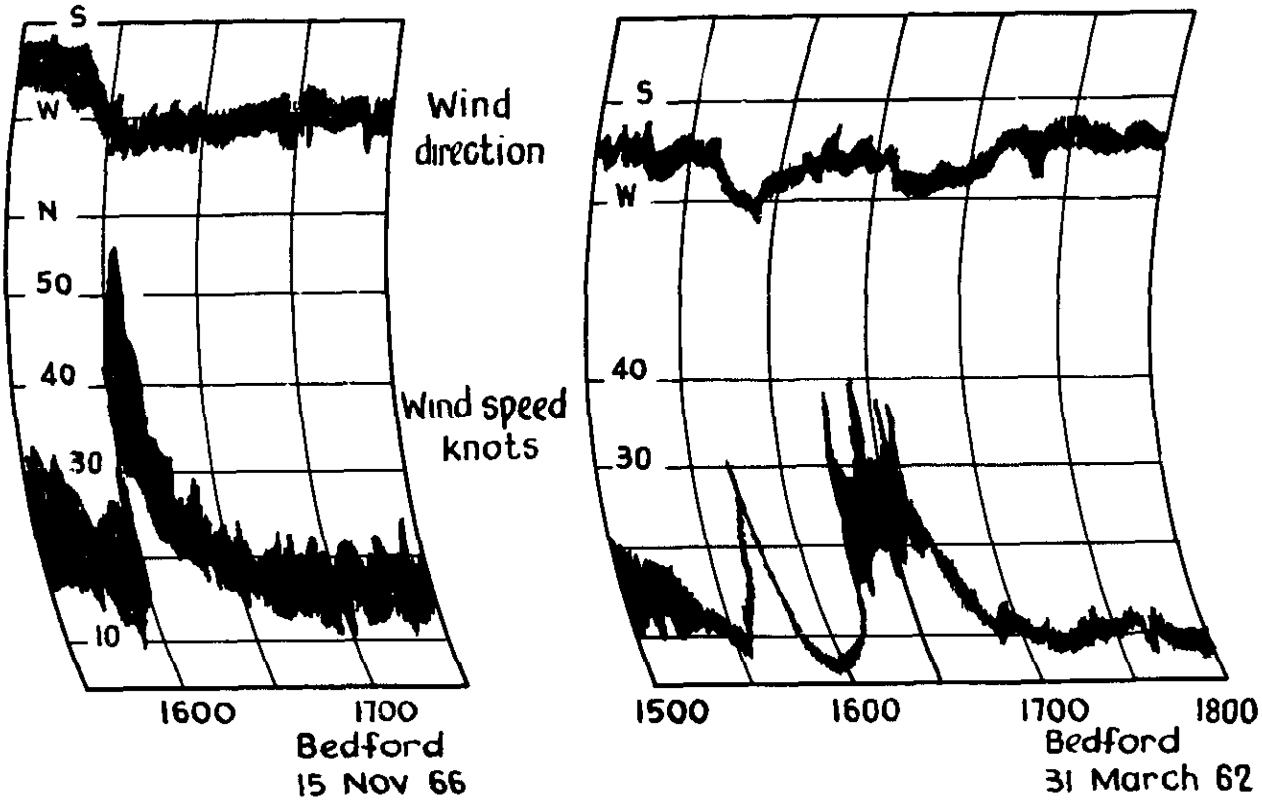


Fig. 13 Anemograms of squalls recorded at Bedford

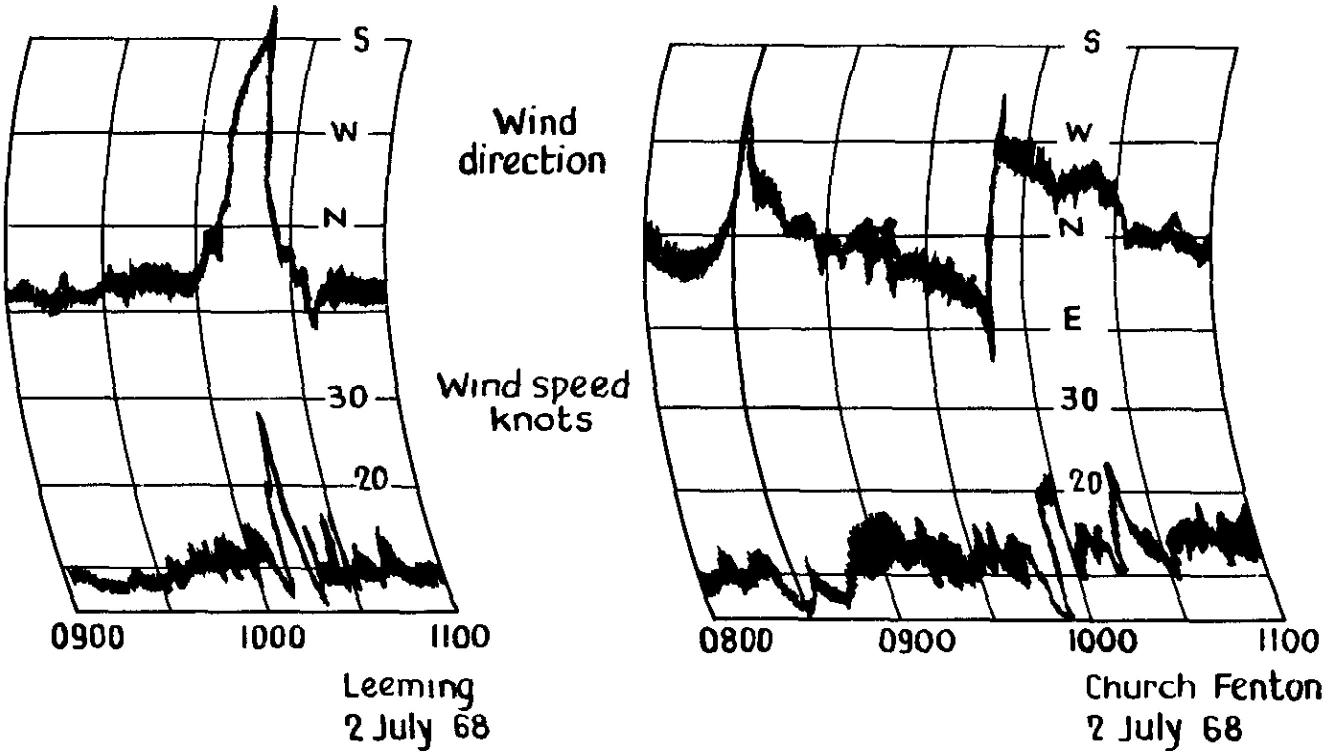


Fig 14 Anemograms of squalls showing marked wind changes

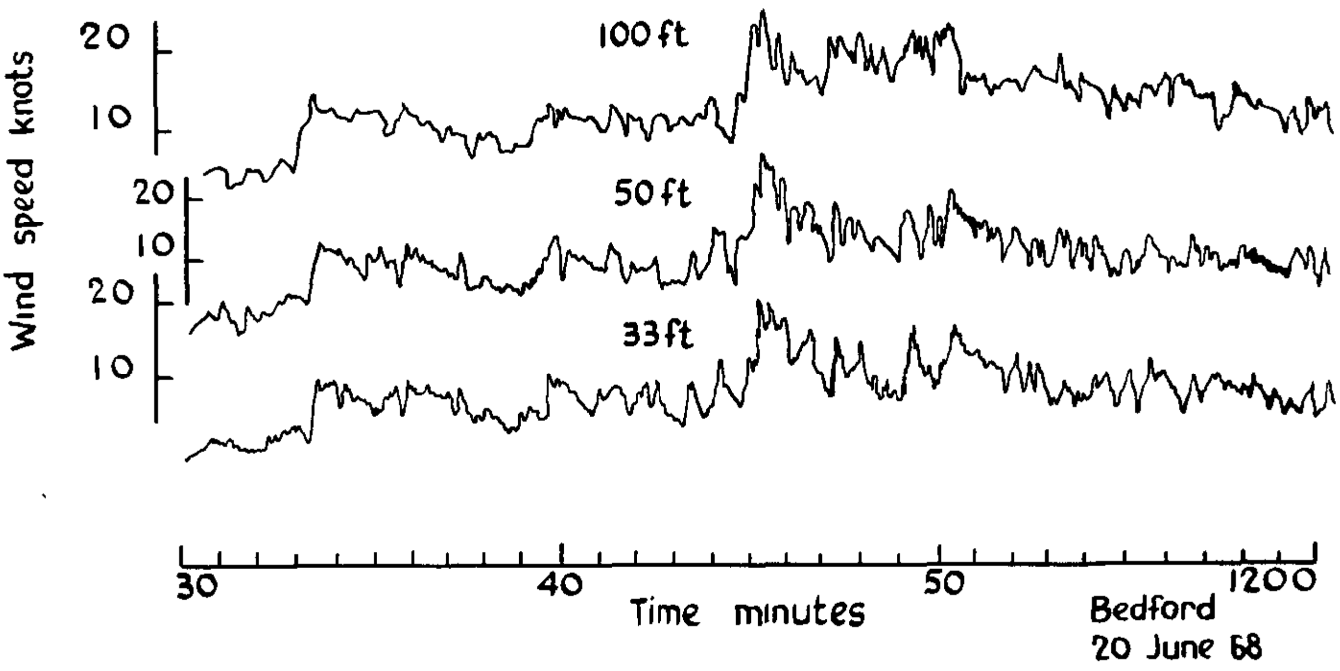


Fig. 15 Time history of wind speed during a squall at Bedford

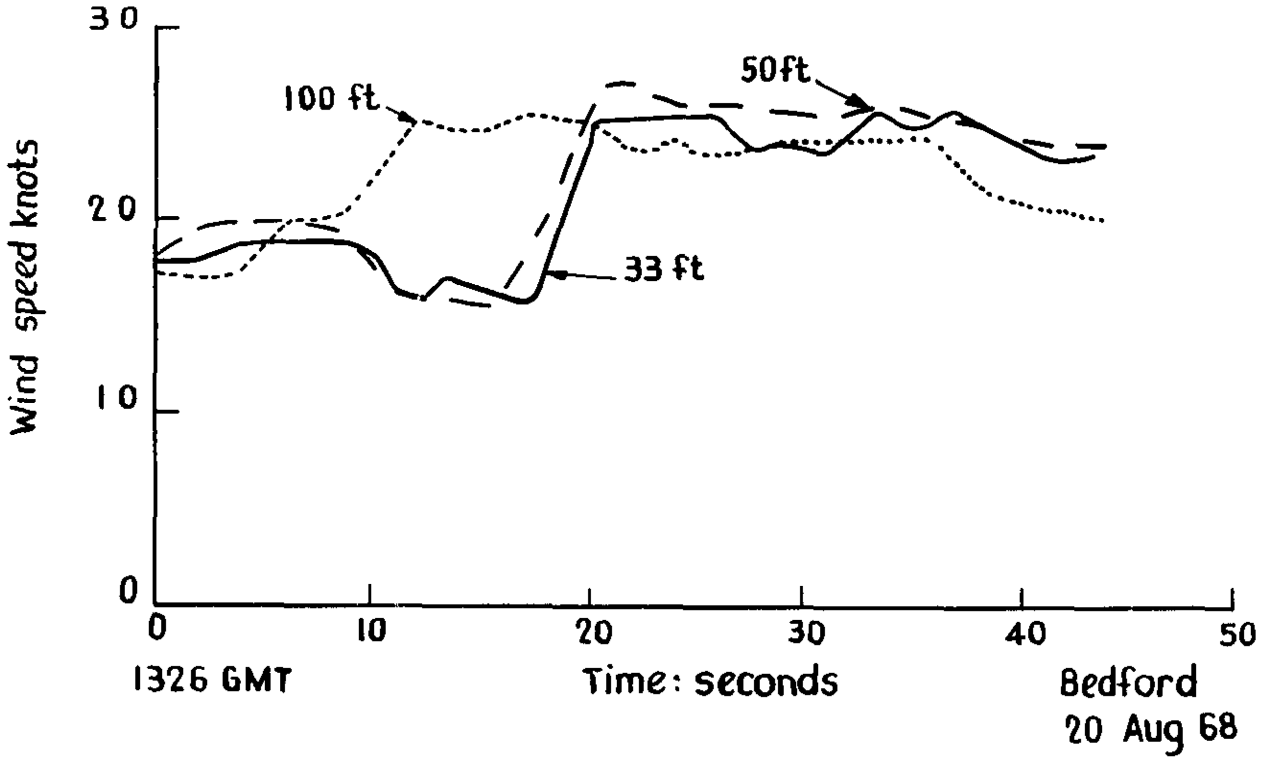


Fig 16 Time history of a rapid change of wind speed

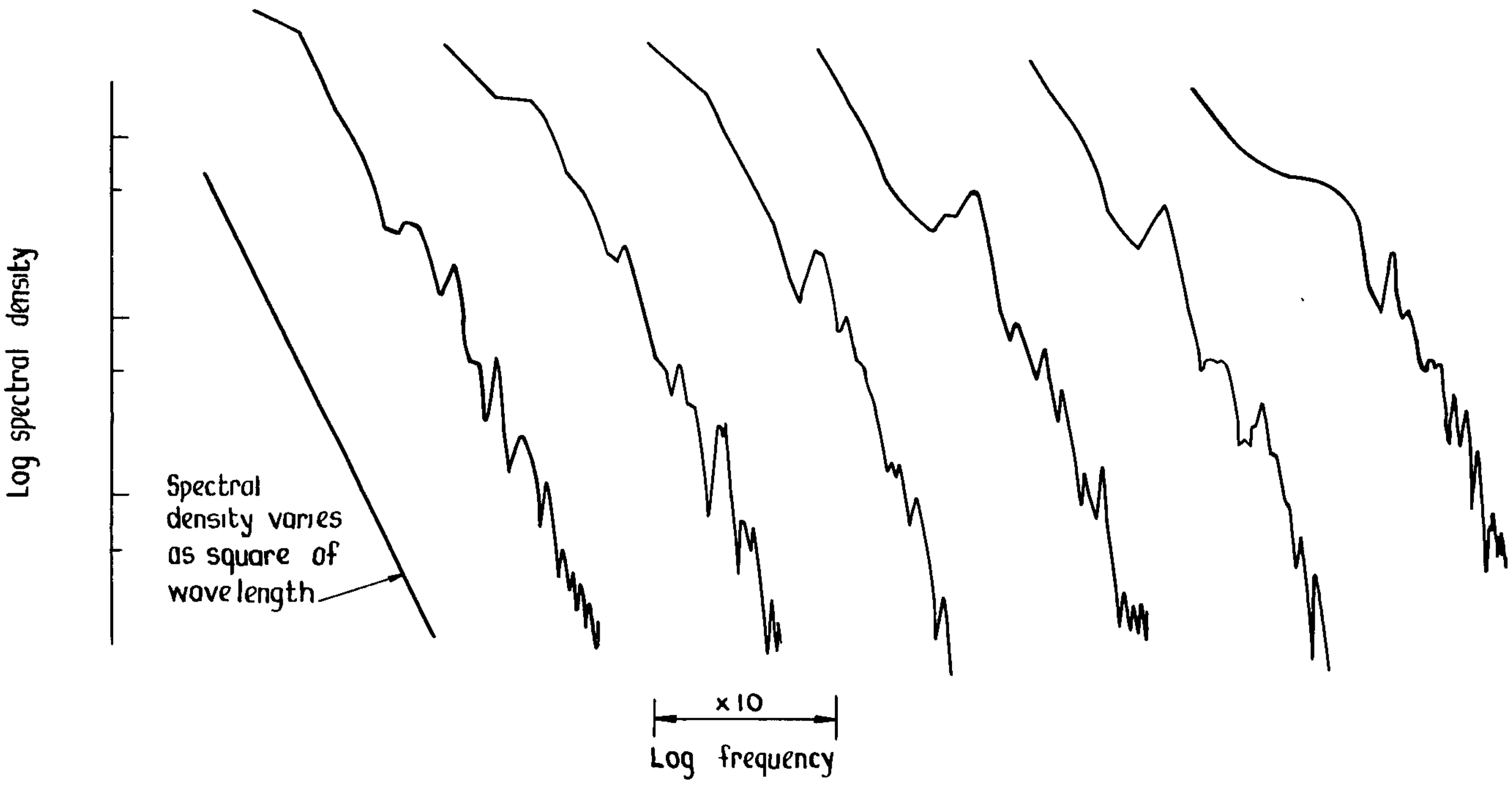


Fig.17 Shapes of spectral densities of true vertical gust velocity measured during flights through thunderstorms

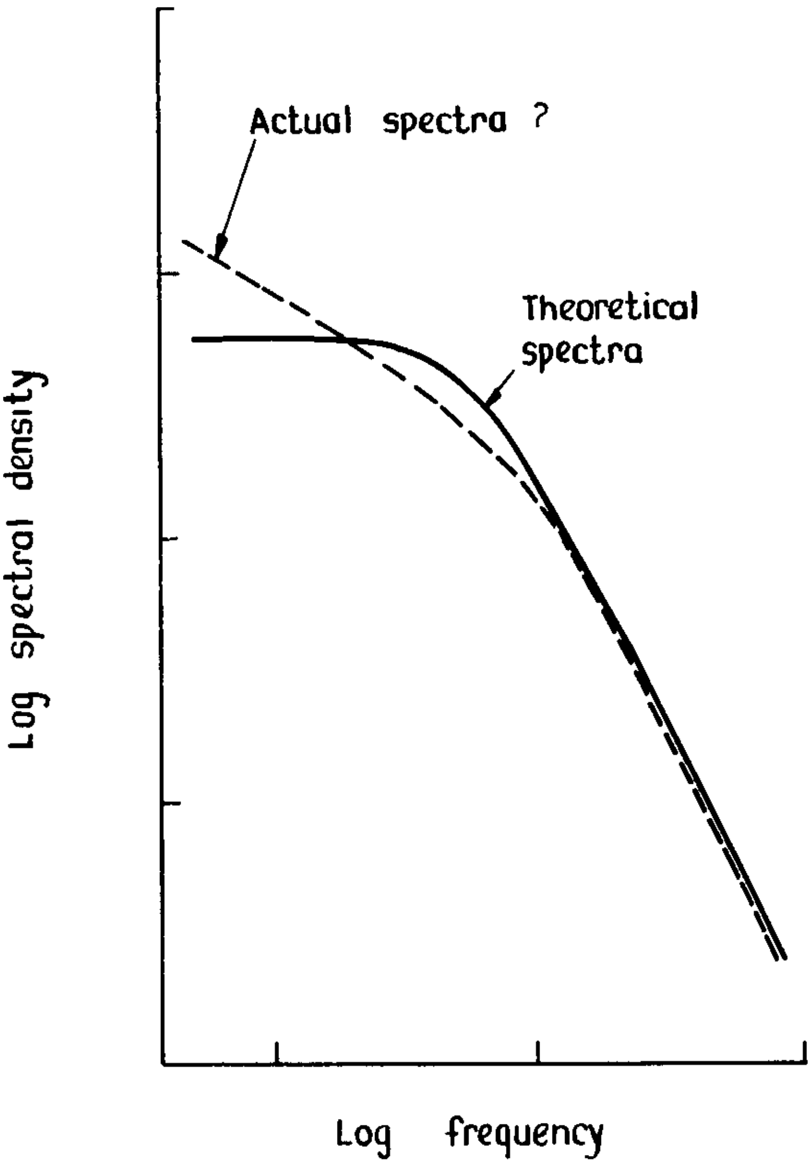


Fig.18 Shape of 'theoretical' gust spectra compared with possible shape of actual spectra at long wavelengths

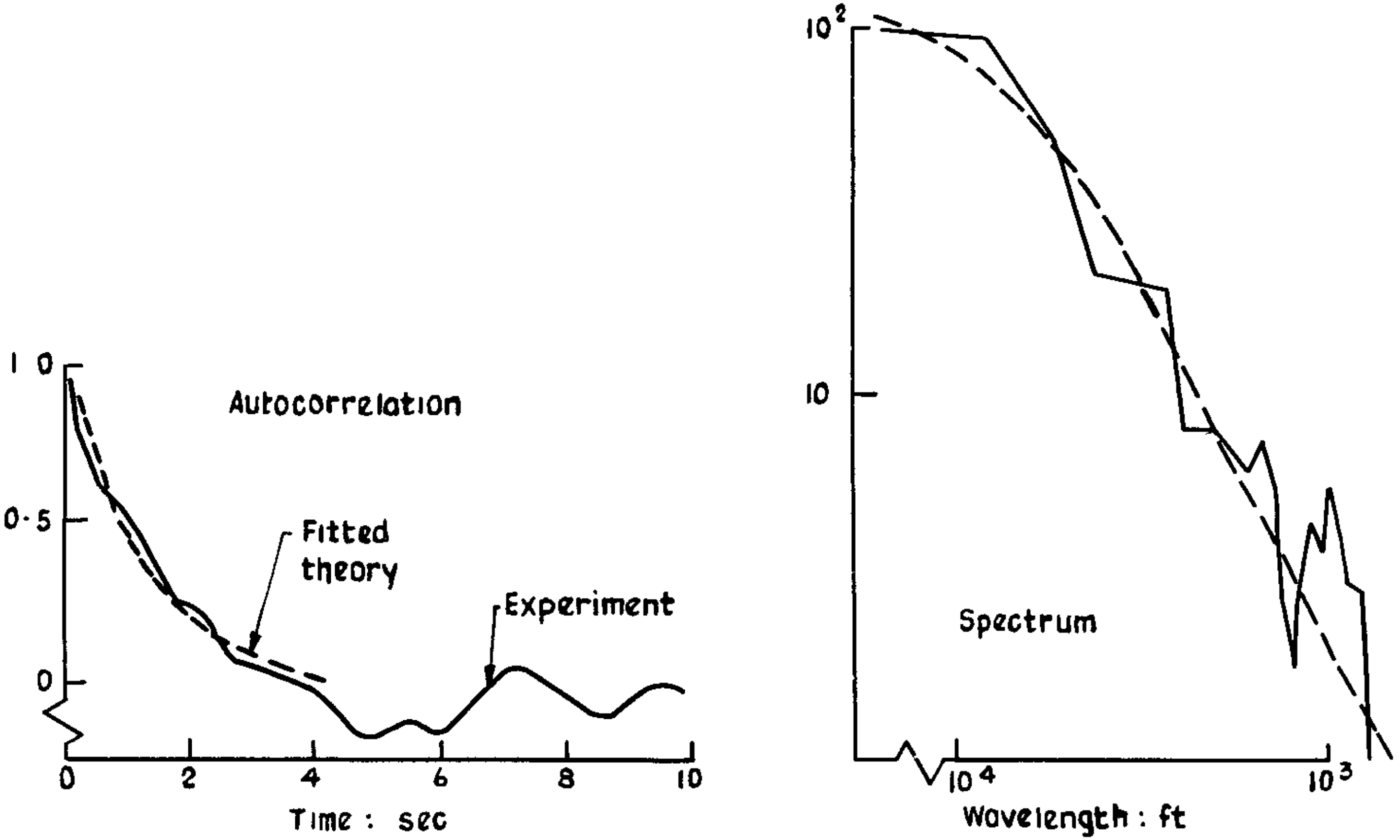


Fig.19 Experimental gust autocorrelation function, fitted theoretical curve and corresponding spectral densities

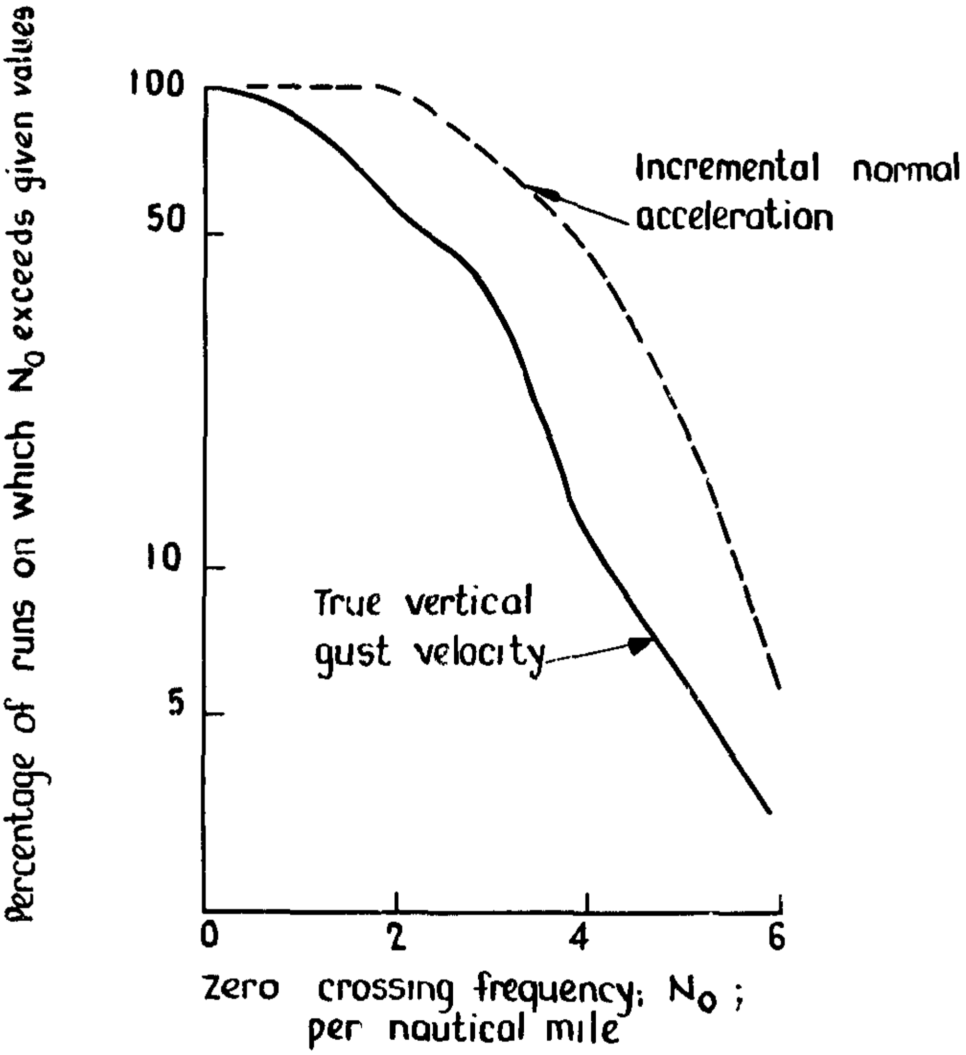


Fig 20 Percentage of runs on which zero crossings of true gust velocity and incremental normal acceleration exceed given values, obtained on flights through convective clouds

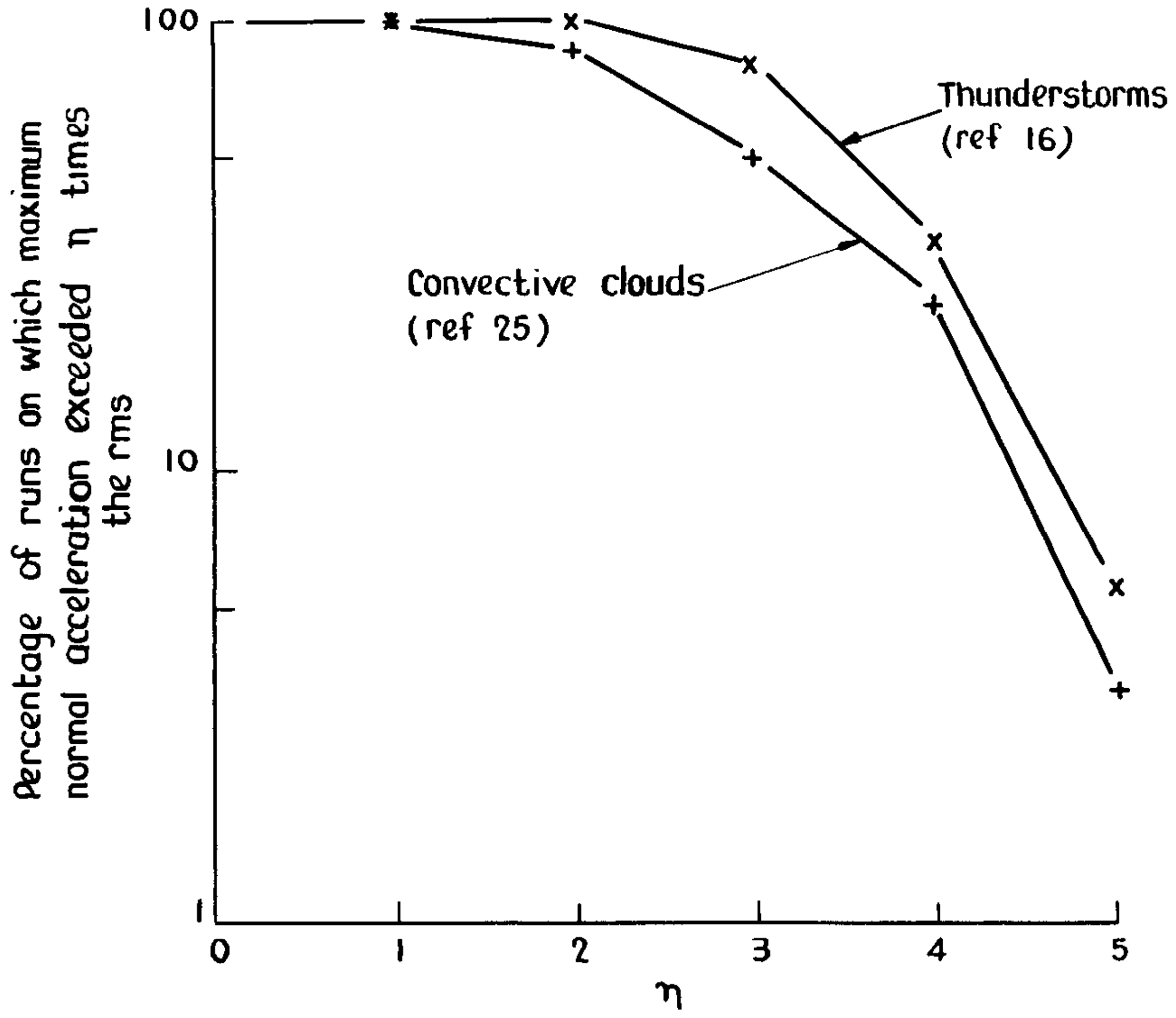


Fig 21 Percentage of runs through convective clouds and thunderstorms on which the maximum normal acceleration exceeds η times the rms

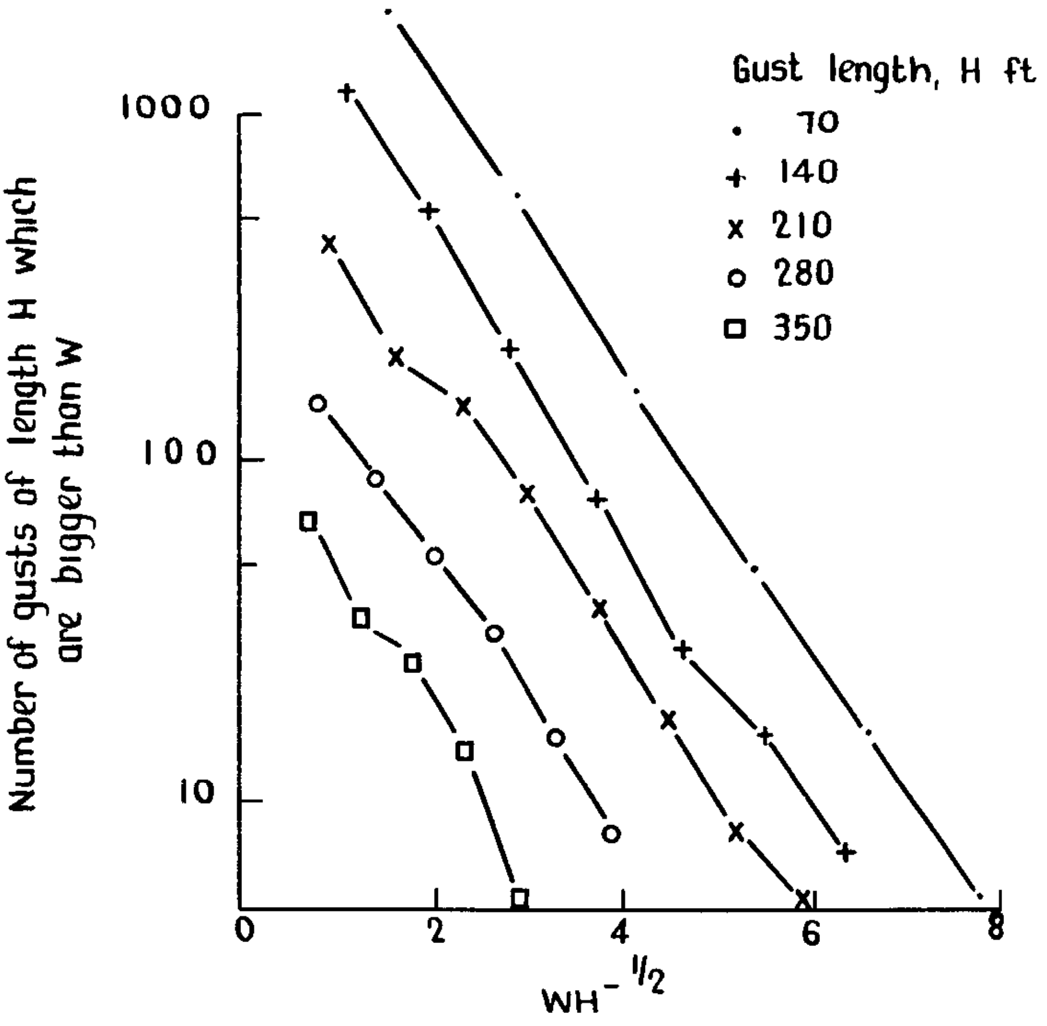


Fig.24 Number of gusts of length H which are bigger than W, for data from ref 27

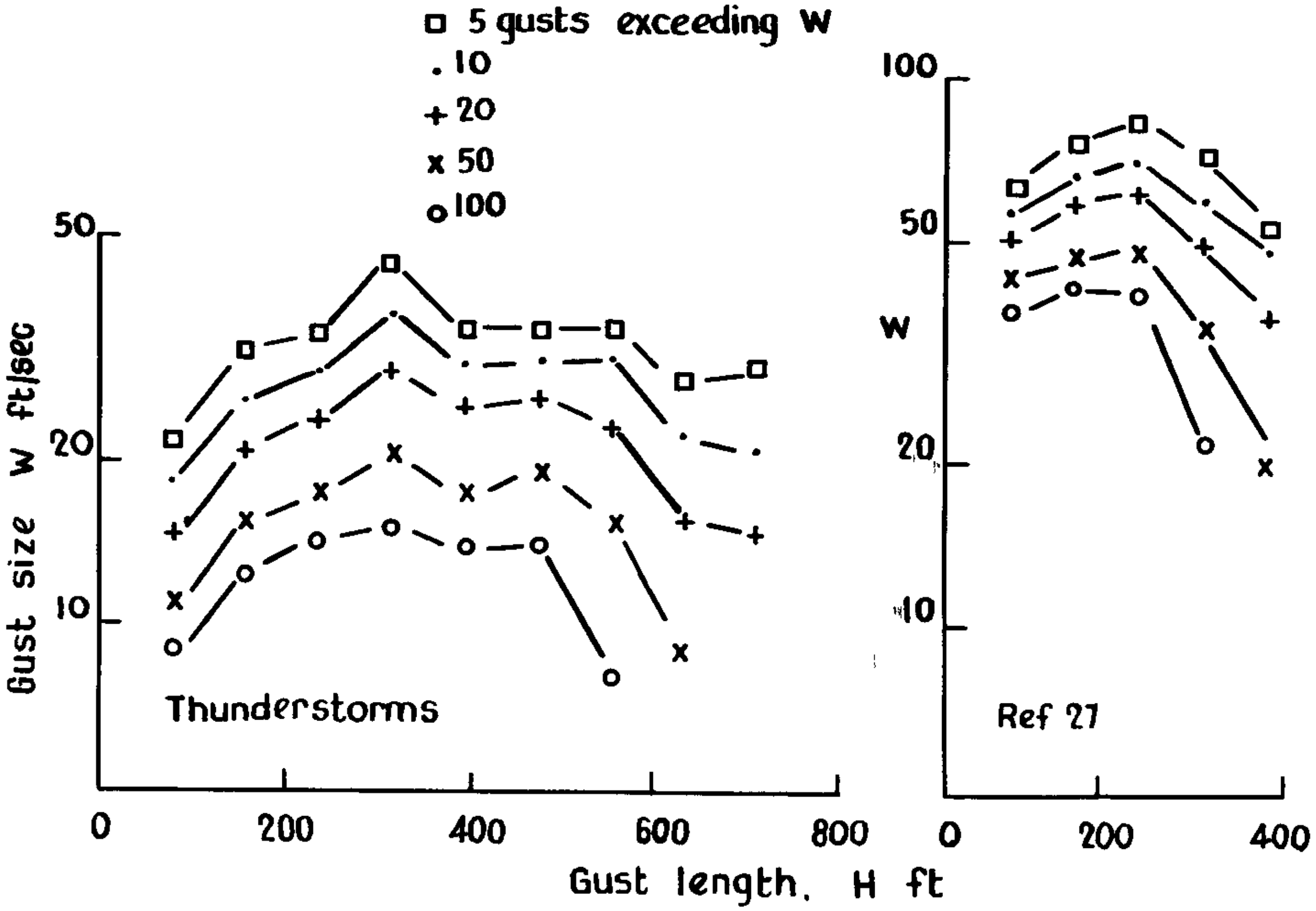


Fig. 25 Variation with gust length of number of gusts of a given size encountered

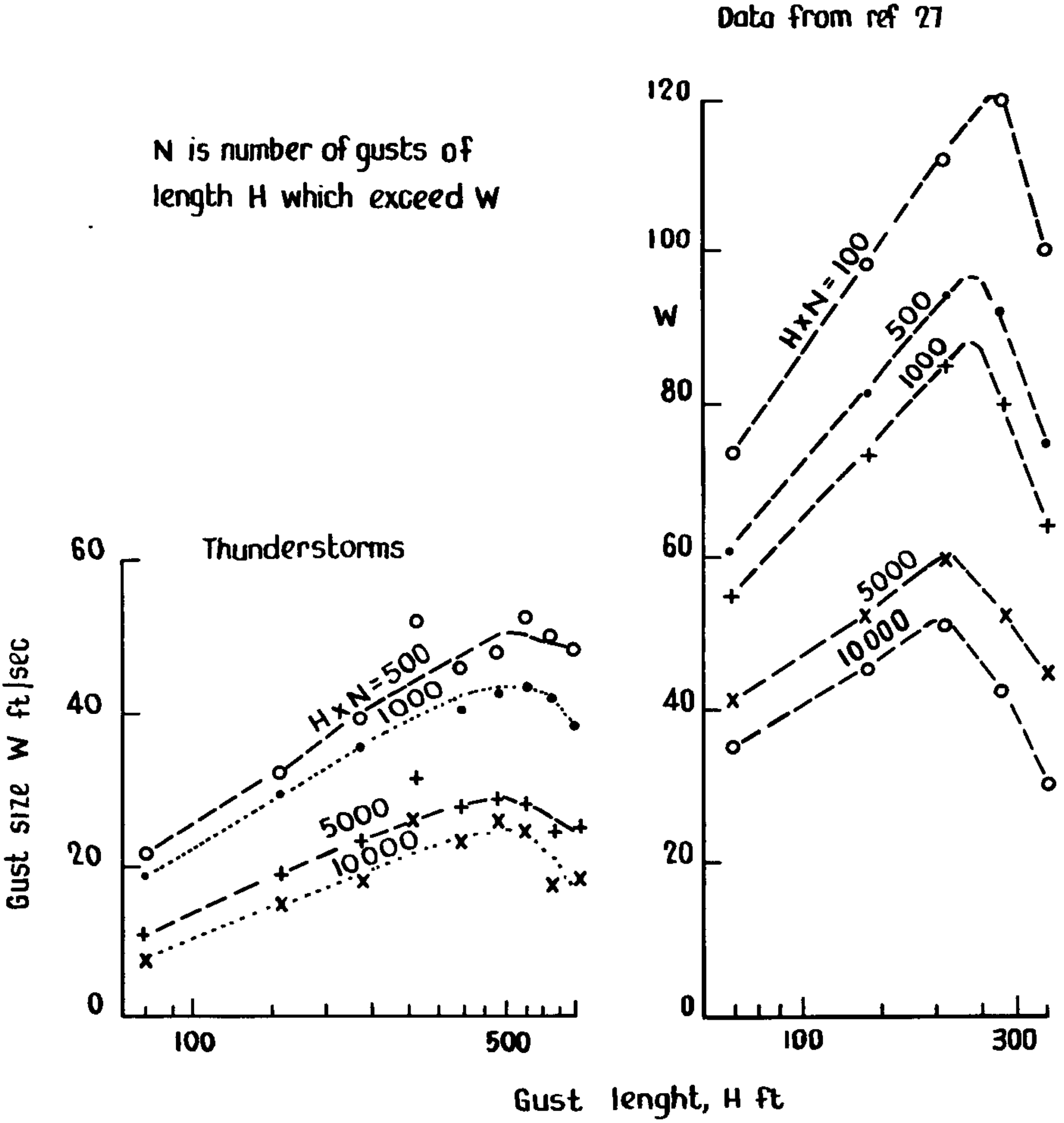

N is number of gusts of length H which exceed W

Fig.26 Variation of gust size with gust length for constant values of the product of gust length and the number of gusts of that length exceeding W in size

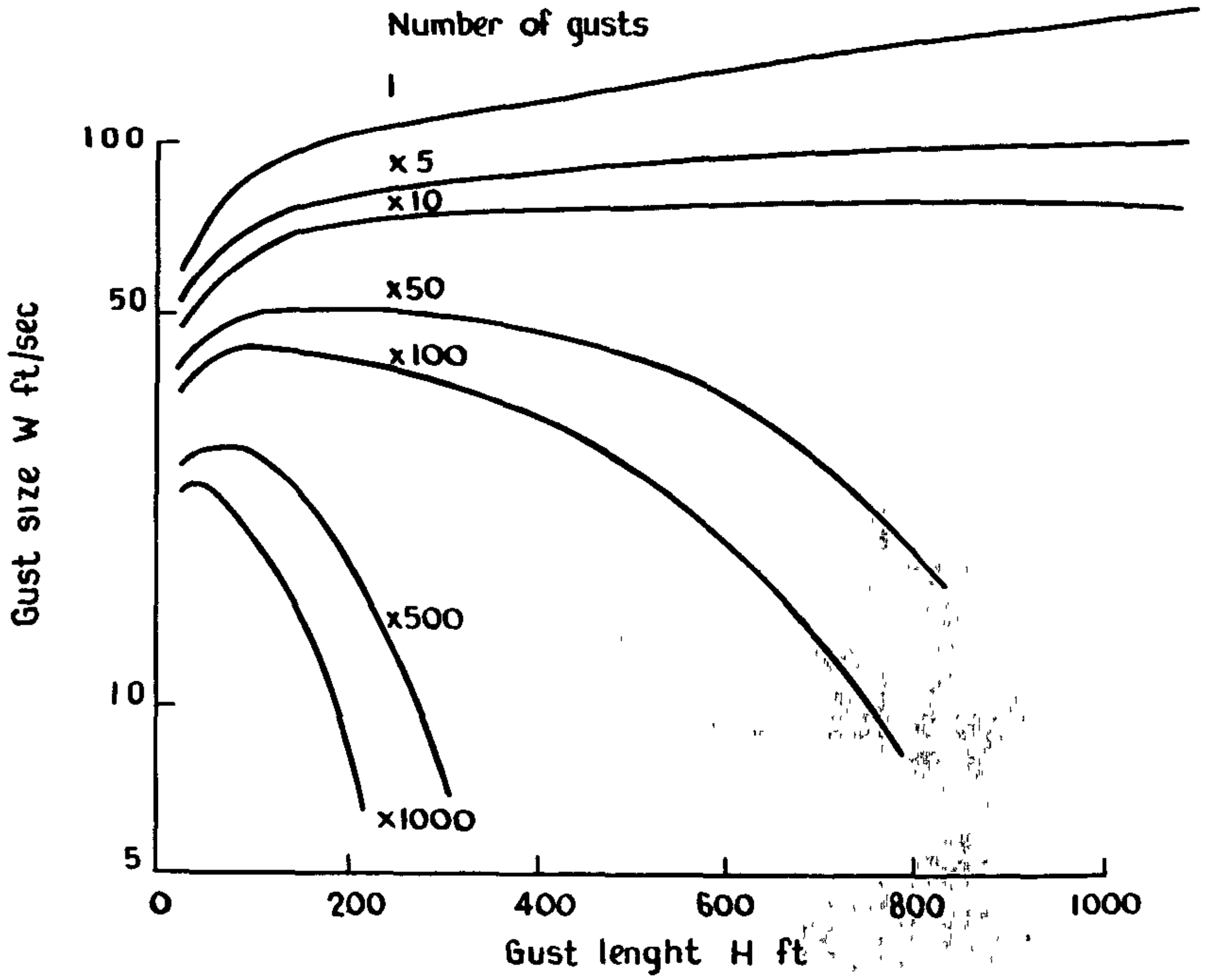


Fig. 27 Variation with gust length of number of gusts of a given size for self-similar gusts with a spectral density which varies as the square of wavelength and exponential probability distribution

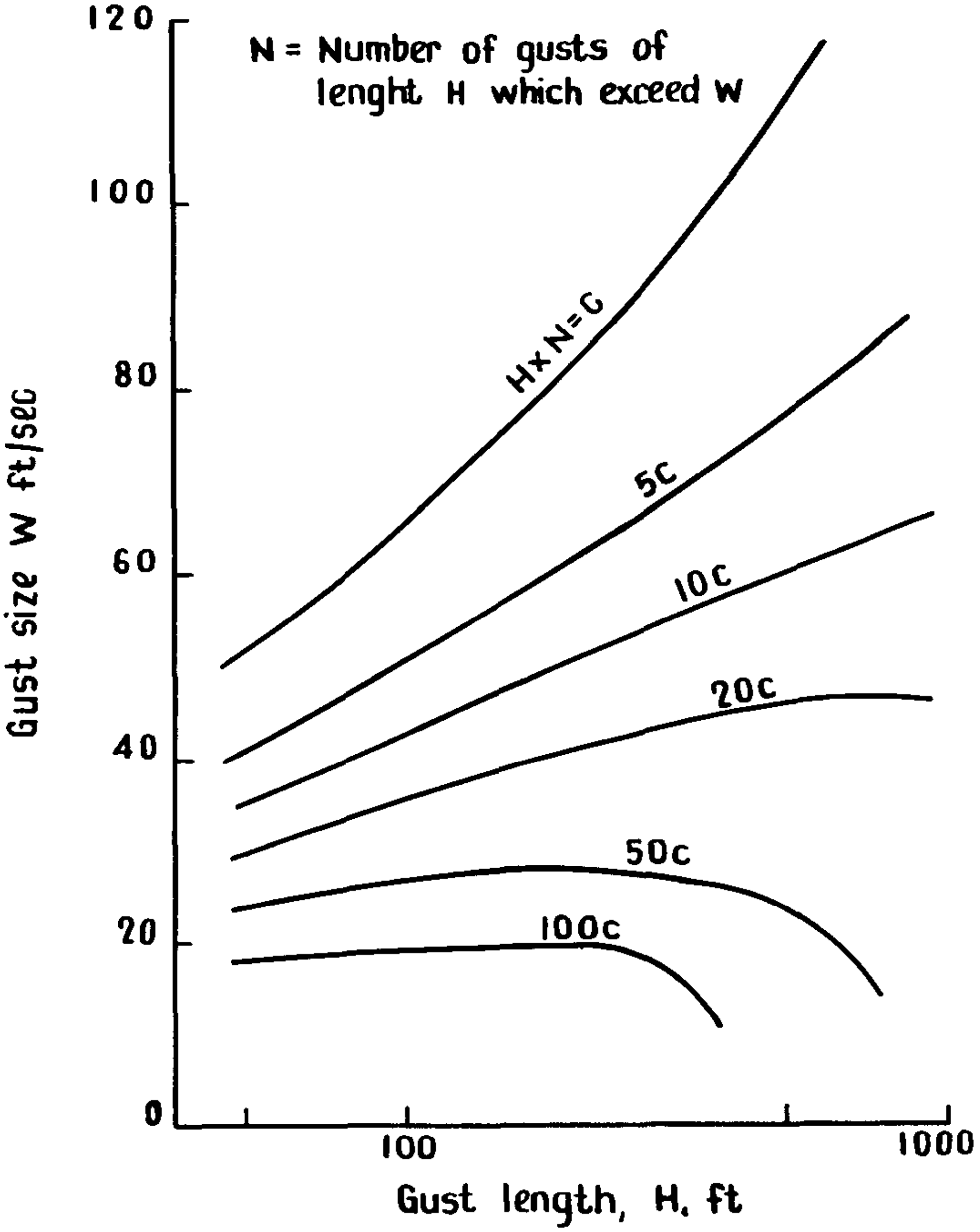


Fig. 28 Variation of gust size with gust length for constant values of the product of gust length and the number of gusts of that length which exceed W in size, for self — similar gusts with a spectral density which varies as the square of wavelength and exponential probability distribution

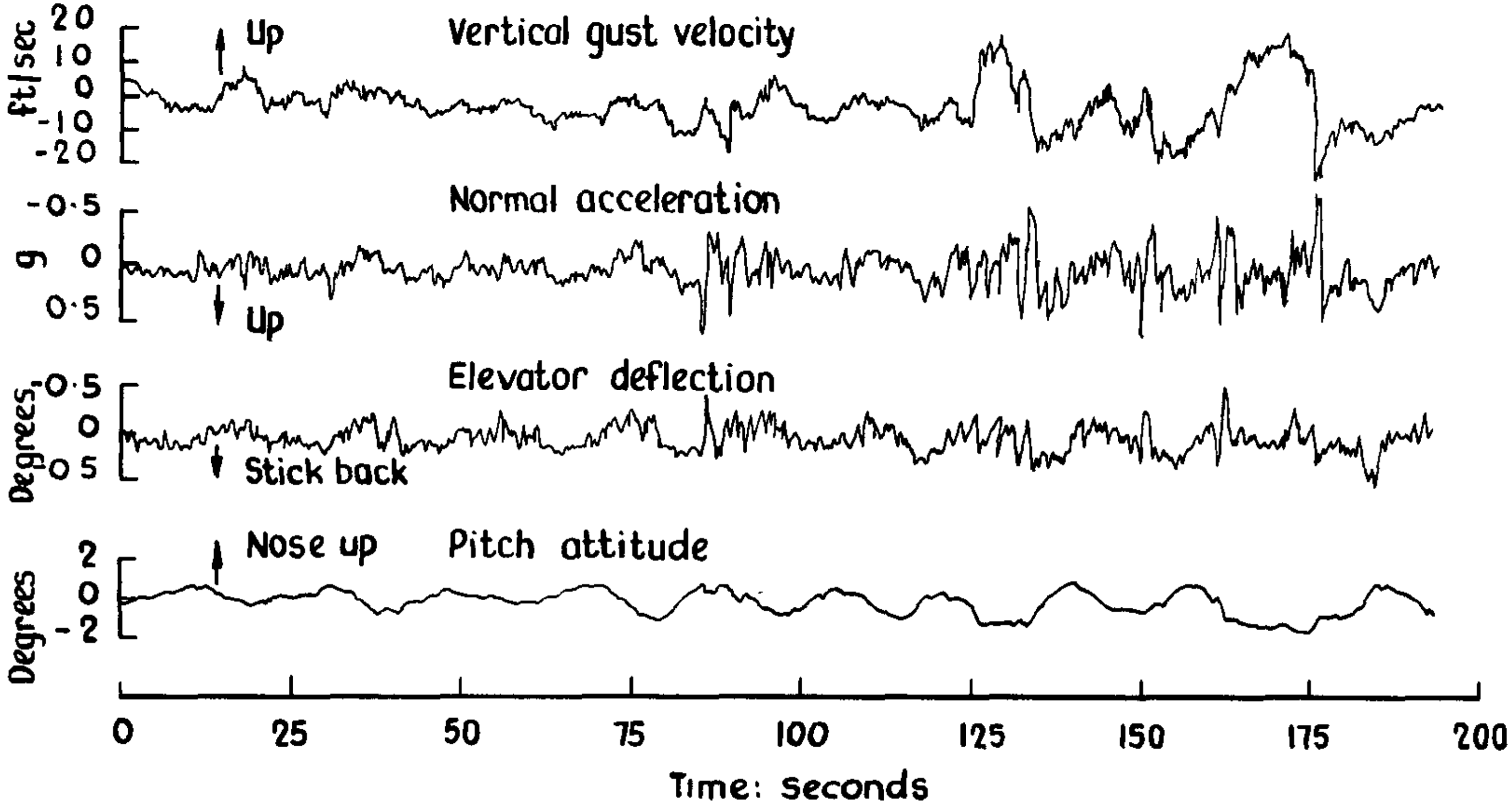


Fig. 29 Time—histories of true vertical gust velocity, normal acceleration elevator deflection and pitch attitude, measured during flight through a convective cloud

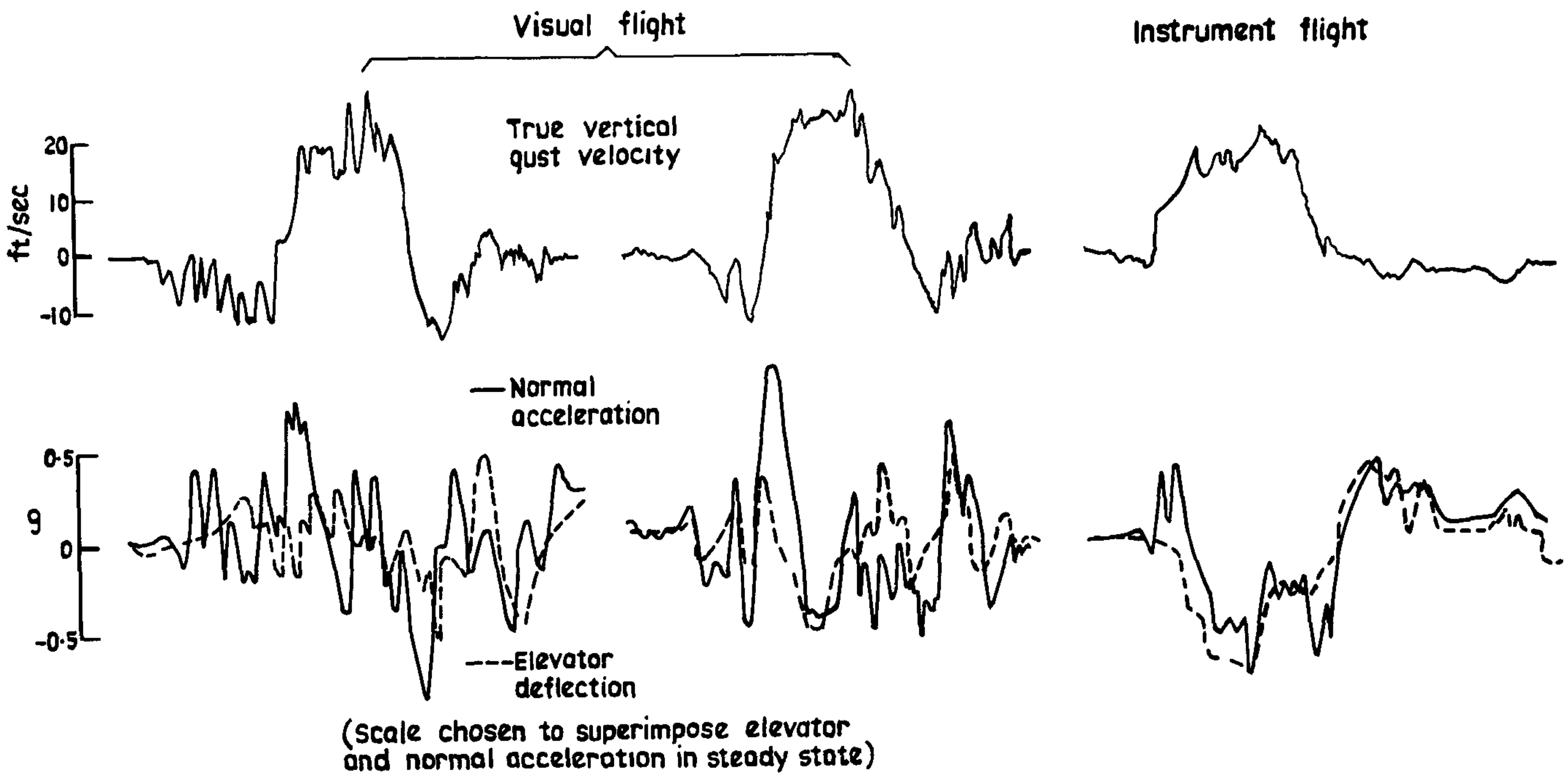


Fig.30 Comparison of incremental cg normal acceleration and elevator deflection for instrument and visual flight by the same aircraft and pilot through similar gusts

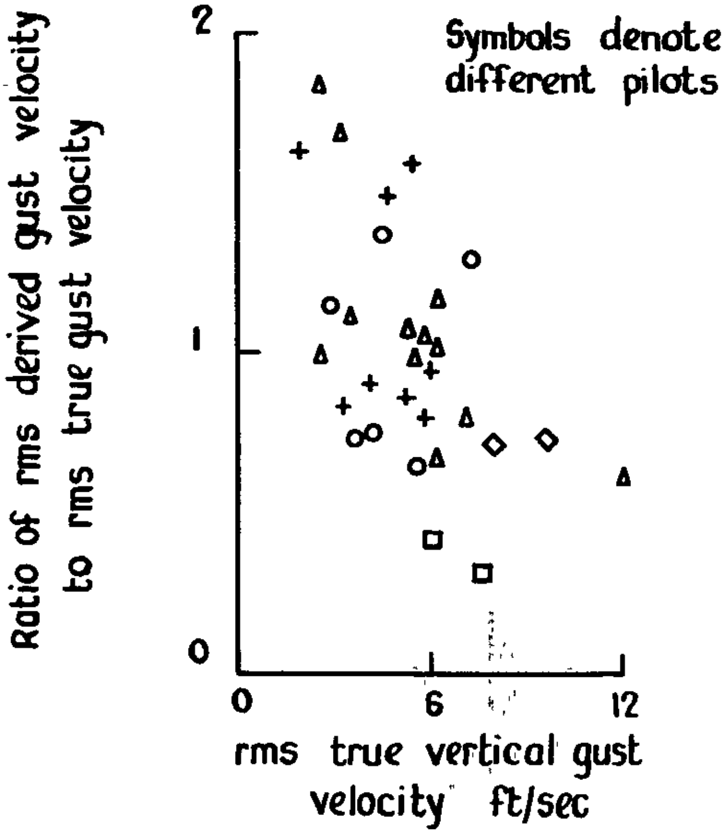


Fig.31 Ratio of rms derived gust velocity to rms true gust velocity vs rms true gust velocity, for flights by different pilots through convective clouds

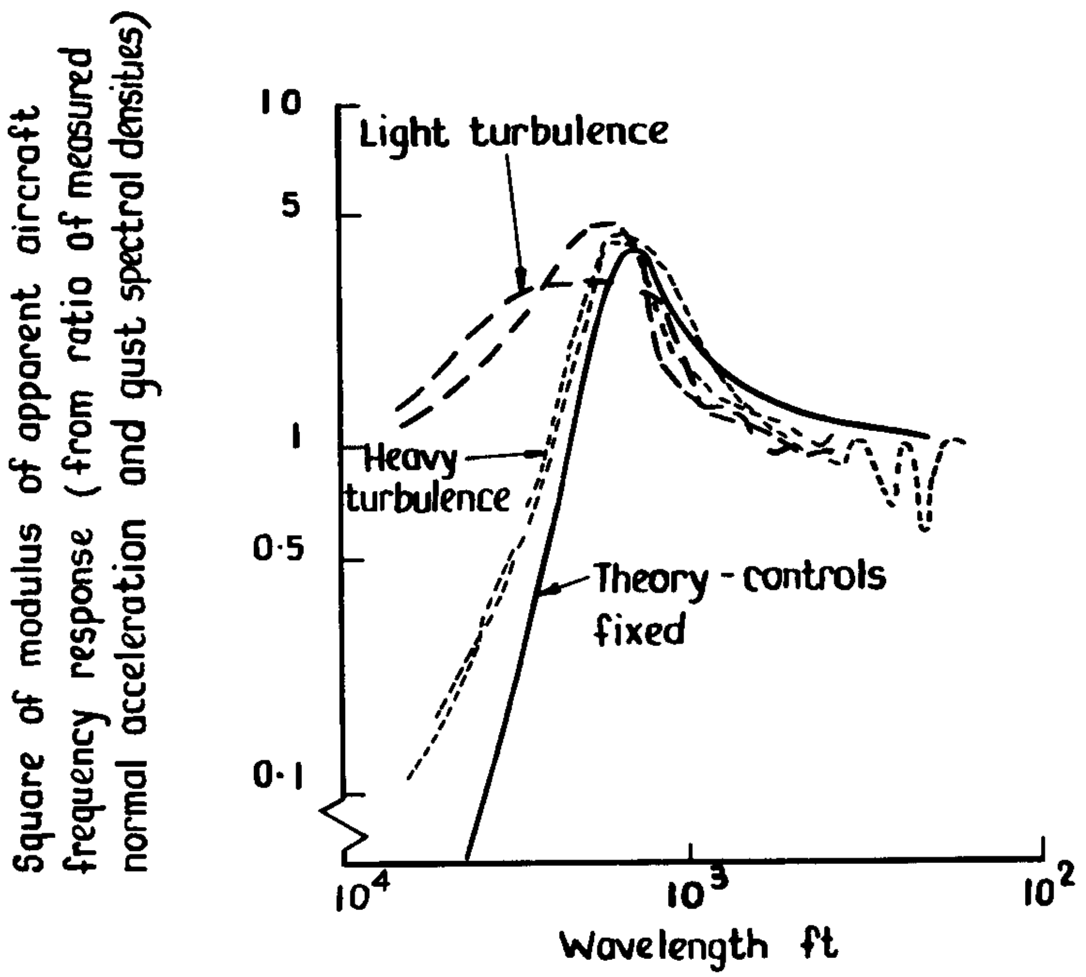


Fig.32 Effect of turbulence intensity on square of modulus of apparent aircraft frequency response (from data in ref 57)

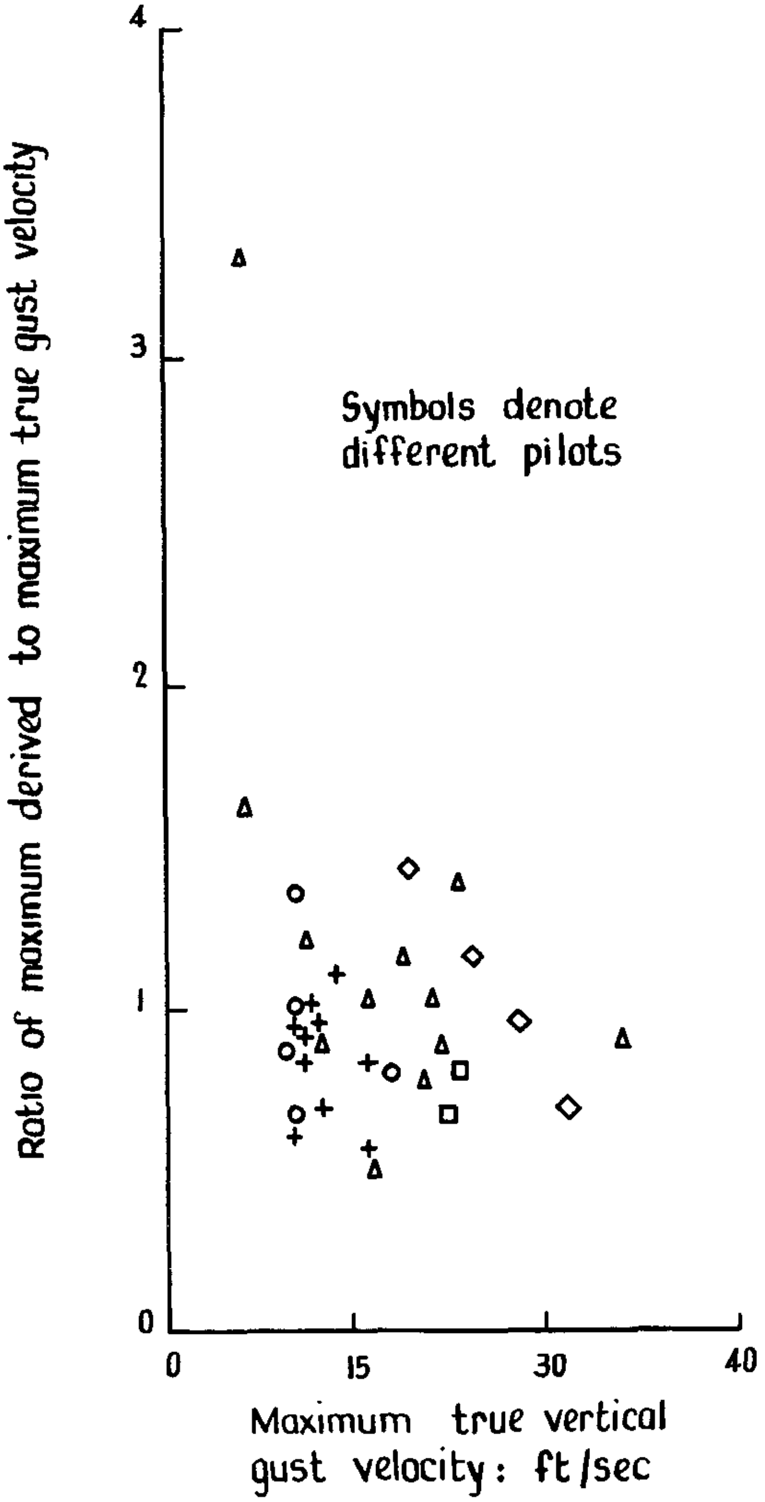


Fig.33 Ratio of maximum derived gust velocity to maximum true gust velocity vs maximum true gust velocity for flights by different pilots through convective clouds

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