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A Study of
TORNADOES IN BRITAIN
WITH ASSESSMENTS OF THE GENERAL TORNADO RISK POTENTIAL AND THE SPECIFIC RISK POTENTIAL AT PARTICULAR REGIONAL SITES

Prepared for
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TORNADO AND STORM RESEARCH ORGANISATION · TORRO ·

SUMMARY

The highest wind-speeds of potential danger to man's structural environment occur naturally in the inflowing circulation of devastating tornadoes.

Tornadoes occur in all continents, but most commonly and most severely in those zones where warm humid airmasses and deep cold airmasses frequently meet. Europe has such a zone stretching from the central Atlantic coast eastwards through France and Germany towards Russia. The severest tornadoes are comparable in intensity to the worst North American ones, but their frequency is lower. On the northern side of the European severe-tornado zone lie the British Isles, the southern half of which has a high incidence of tornadoes. This is due partly to geographical situation and partly to an inherent susceptibility to tornado development at all seasons.

This study reports on the incidence and strengths of tornadoes in Britain. The main objectives areto give an overall view of the nature of British tornadoes throughout the whole country, and to calculate conservatively the probabilities with which various high wind-speeds are reached in particular regions of interest.

For these purposes use is made of a comprehensive data bank based on 1500 tornado cases covering the period AD 1091 to 1984. The tornado data are analysed in time and space and the results depicted using tables, graphs and maps. Intensities are assigned on the basis of the Beaufort-based T-scale of tornado strengths concerning which a full explanation and reference set of photographs are provided.

Britain's tornadoes are mostly low-to-moderate in strength. The severest tornadoes are not as strong as on the Continent. Nevertheless, tornadoes in the southern part of Britain are very numerous. When Britain is divided into two zones, an outer northern/western zone and a southern zone, the latter is found to have 20 times more tornadoes than the former. These zones, and some smaller ones besides, are studied for their tornado frequencies in terms of their intensity ranges, thus providing fundamental intensity-occurrence relationships. Path lengths, path widths and directions of incidence are discussed, and the mean damage areacomputed as a function of tornado intensity.

This permits the tornado wind-speed probability relationships to be established using the McDonald, Mehta and Minor method which allows for gradations of intensity and damage potential via a combined Rankine vortex model for the wind-speed profile. It is then possible to calculate conservatively the risk of different tornado wind-speeds happening at specific locations. These include coastal regions of the counties of Sussex and Suffolk. Calculations of pressure drops and rates of fall of pressure associated with tornadoes are also made.

For the East Suffolk coastal area the chief features of a design-basis tornado are to be found in sections 5.11 and 5.13. The parameters include, at the 10^{-4}/year probability level of occurrence, a maximum tornadic wind-speed of 60 m/s and a joint maximum horizontal wind-speed of 63.5 m/s. The report concludes with remarks on missile generation,a summary of the principal results (Section 5.15, pages 113-115), and an appendix of British tornado case-histories.

CHAPTER 1 - INTRODUCTION AND OBJECTIVES

This report on tornadoes in Britain has been prepared with the aim of assessing the general and comparative risk potentials concerning tornado occurrences and intensities in Britain and the specific risk potential in certain regions. The results, which are presented and discussed in various ways, include computing return periods and probabilities with which certain wind speeds are likely to recur.

The request has been made by Her Majesty's Nuclear Installations Inspectorate because of the need to ensure that possibly storm-vulnerable structures, containing nuclear plant or other fissile and radioactive materials, should not be exposed to a greater risk from wind-initiated damage than is reasonable with regards to public safety. For some years the International Atomic Energy Agency has been preparing and publishing an extensive series of Codes of Practise and Safety Guides covering all aspects of nuclear safety standards. Guide number 50-SG-S 11 A, on "Extreme Meteorological Events in Nuclear Power Plant Siting", considers the dangers posed by tornadic phenomena (pp 18-22, 49-59). It recommends that regulatory authorities responsible for commissioning nuclear plants should assess the existence of tornado potential in their own countries, and, if significant, compile a regional tornado inventory to establish the intensity and frequency characteristics, and hence the strike probability for different levels of intensity. This will permit the design engineers to make use of a design-basis tornado corresponding to the chosen level of risk denoted by the strike probabilities.

In Western Europe the only research body which has made a conscientious and thorough job of amassing data on tornadic phenomena is the Tornado and Storm Research Organisation (TORRO). Indeed, TORRO was specifically set up, in 1974, for that purpose. A brief history of the Organisation, which also now has thunderstorm, hailstorm, weather disaster, and ball lightning divisions, can be found elsewhere (Meaden, Rowe, Mortimore and Elsom 1985). In its numerous publications since 1974, TORRO has amply demonstrated that the incidence of tornadoes over much of England and parts of

Wales is so great that a serious inquiry into the tornado risk to structures is called for, and the present survey is based on the evidence provided by 1500 British tornadic incidents.

In France a report has recently been completed by Professor Jean Dessens on the basis of a study of 100 French tornadoes (Dessens 1984). Tornadic intensities were estimated and the geographical distribution plotted. Hourly, monthly and annual frequencies were determined, as also directions, path widths, lengths and areas. No regression line could be obtained, so no probabilities could be calculated. Instead, a simple estimate of tornado frequency was made using only the 1960–1983 data. For the higher risk zone which included northern France, it was considered that buildings requiring a high degree of protection like "nuclear centres" should be made to withstand winds of 300 km/h (83 m/s, 188 mph). An allowance of 50 mb was thought necessary for possible rapid pressure drops. For France as a whole one tornado a year can be expected to reach or exceed an intensity of T5 or F3. The severest French tornadoes of the century appear to have attained intensities of T10 or F5. (Note : the T- and F-Scales of tornado intensity are discussed in chapter 3 ; see also the Glossary).

1.1 OFFICIAL WIND-SPEED ESTIMATES

In Britain the official wind-speed estimates used in engineering and building design have been based, traditionally, upon conventional wind-speed data. The latter, gathered from official anemometer or anemograph records over many years, refer to actual measurements, i.e. actual extremes and means, obtained under conventional conditions of exposure (namely at 10 metres above level ground in an open country situation). The resulting statistics have been summarised in official maps, such as the one reproduced in Figure 1 (British Standards Institution, 1972).

This figure provides the maximum 3-second gust speeds likely to be exceeded on average once in 50 years for open, level-country exposure 10 metres above the ground. The map was prepared by making use of the known extreme wind-speed data from a few dozen stations with accurate operating periods of up to 50 years or so. Therefore, one should be cautious about extending such estimates to periods of time considerably longer than this. Nevertheless the need exists, especially for the various bodies which are concerned with or responsible for, public safety, economical construction costs, and structural endurance.

In Great Britain the design wind-speed, i.e. the wind-speed for which structures are designed for safety, at each of the existing and proposed Nuclear Power Stations depends upon the geographical location of the reactor site, with corrections applied for the nature of the local topography and the heights and shapes of nearby buildings. Thus, the maximum speed envisaged for the site of Torness, on the east coast of Scotland, is 68.3 metres/sec (153 mph). The C.E.G.B. has declared that this may be expected to occur only once in 10 000 years.

In south-eastern England the extreme wind-speeds experienced are lower, as are the estimated long-period extremes. For example, at Sizewell, on the east coast of Suffolk, the C.E.G.B. has stated that 58.8 m/s (132 mph) should be employed in the design of its most sensitive buildings - also with a supposed 1 - in - 10 000 year return period (C.E.G.B., P11).

The windiest parts of Britain, in terms of mean wind-speed over extended time intervals such as one hour, one day, one month, etc, are found around Britain's western and northern coasts, and on the highest mountains. These are also the areas likely to have the highest gust-speeds during the course of general gales (Figure 1). The windiness of these regions arises from their proximity to one of the most-frequented depression tracks of the world, and their exposure to the open Atlantic Ocean during the associated westerly gales. By contrast, the least windy parts in these cyclonic situations are the more sheltered southern and eastern counties of England, including Suffolk and Essex (Figure 1).

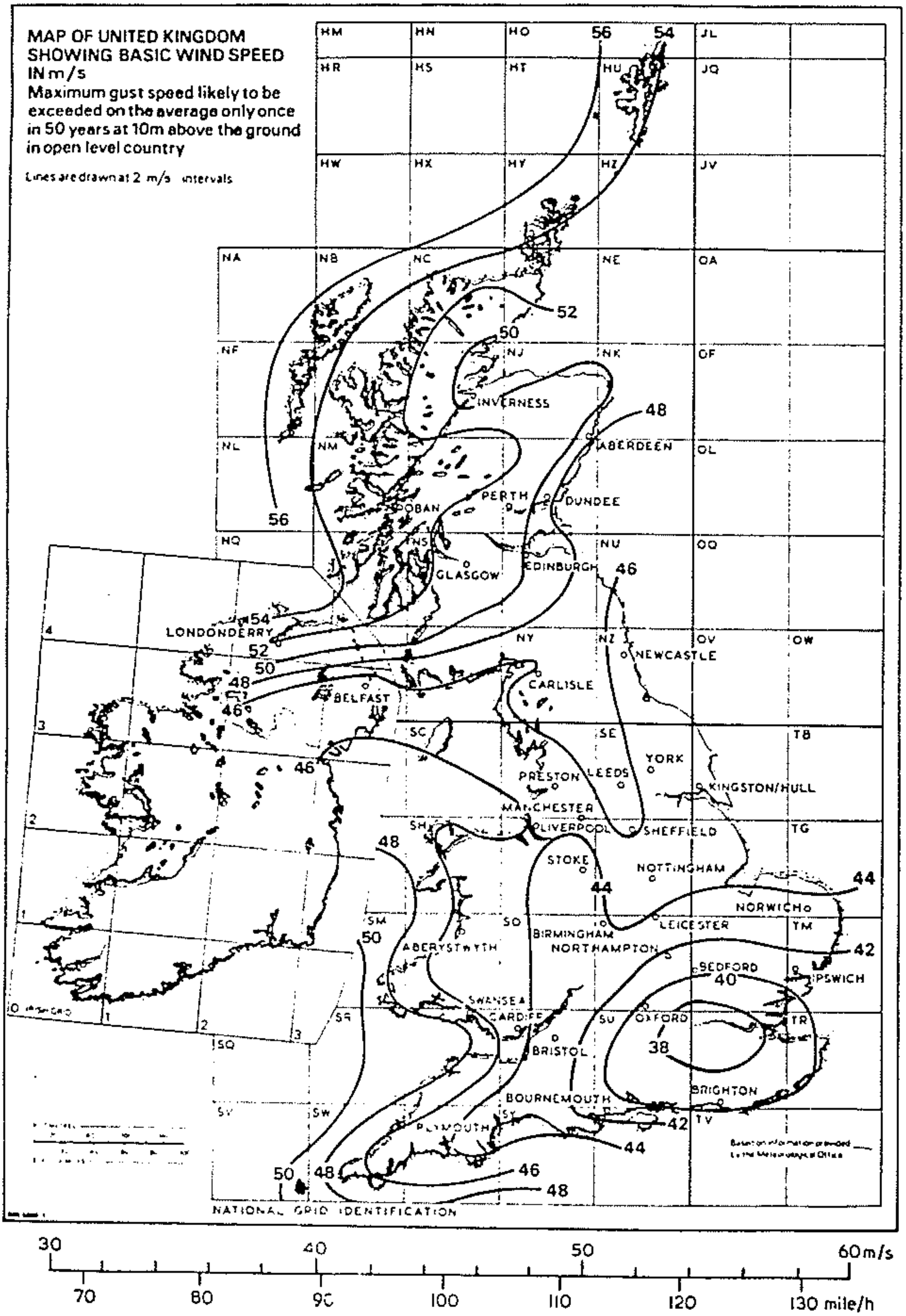

Fig. 1. Basic wind speed

1.2 THE TORNADO FACTOR

The traditional estimates ignore the influence that tornadoes may have on the long-term maximum gusts, and hence the wind-loading probabilities. This is despite the knowledge that the greatest wind-speeds reached in nature occur in tornado systems. The contribution made by tornadoes appears to have been overlooked because, until recently, most meteorological textbooks and official sources have continued to claim without justification that "tornadoes seldom happen in Britain". Also, it may have been supposed that, because the areas swept out by individual tornadoes are small, the associated risk is small enough to be neglected.

These fallacies have been exposed through the 10 years of data collection and research undertaken by TORRO in preparing its data-bank of British and continental European tornado cases. TORRO has shown that Britain is one of the most tornado-prone countries of the world in terms of documented annual tornado events per unit area, although admittedly the average British tornado is not a powerful structure-destroying force. Tornadoes are frequent because they mostly develop on cold fronts and instability boundaries associated with Atlantic depressions throughout the twelve months of the year. There is no long tornado-free season as in many other tornado-prone countries. Moreover, multiple tornado outbreaks occur quite frequently.

The total tornado risk (i.e. the probability of tornado occurrence, see Glossary) is therefore not inconsequential, because of the comparatively high tornado density, although each individual damaged area is small. This is particularly true of England and Wales, south and east of the mountains of Wales and Northern England. Hence, tornadoes with their damaging or devastating winds are most numerous in precisely those regions where conventional maximum wind-speeds have been found to be lowest. This accentuates the under-estimate for these areas, so the wind risk to potentially-vulnerable structures in the south and east of Britain is much greater than has been recognised. Whereas this may perhaps not be considered too important for the construction of ordinary housing, commercial buildings, factories, etc, it could lead to serious consequences for structures like the Severn and Humber Bridges (Meaden 1983, 1985) or for supremely sensitive ones like nuclear reactor buildings. (The introduction of a tornado-occurrence factor into the wind-speed estimates at the location of the Severn Bridge is to reduce the conventionally-calculated return period by a third).

In addition, the 1 in 10 000 year estimates which are based on analytical extrapolation of the conventional wind-speed data from 50 years to 10 000 years are questionable because of the intrinsic nature of the suppositions. Moreover, the calculations produce wind-speed figures which are well beyond those accepted as constituting the national records for <u>any</u> part of the country ; that is, the derived results lie in a realm beyond known experience anywhere, a situation which is quite different from the tornado situation, as will be explained in the next paragraph. Thus it is that the Scottish wind-speed record is 64 m/s (144 mph) for Coire Cas in the Cairngorms, whereas the Torness basic design maximum wind-speed is given as 68.3 m/s (153 mph) ; and the English inland <u>record</u> is 47 m/s (105 mph) for Wittering, Cambridgeshire, and the English coastal <u>record</u> is 49 m/s (110 mph) for Scilly, compared with a suggested Sizewell design speed of 58.8 m/s (132 mph). Again, the statisticians have moved into a domain of unachieved wind-speeds through the practise of extrapolating 50-year data to a distant 10 000 year graphical point.

This objection applies less to tornado data when used countrywide on 35-100 year, or 1000 year, accumulated data, because the resulting wind-speed figures which correspond to the required probabilities are necessarily at levels which have been known to happen on many previous occasions elsewhere. For example, it will be shown in this report that tornado wind speeds reaching or exceeding 62 m/s, 137 mph (T5 or more on the TORRO scale as explained in chapter 3) have been known to occur 28 times <u>this century</u> in southern, central and eastern England, and could even have reached 84-95 m/s (187-212 mph) in the devastating T7 tornadoes of 1913, 1937 and 1954. The English inland and coastal <u>measured</u> wind-speed extremes, cited above, are likely to have been surpassed in all 366 tornadoes of force T3 or more in the same period of this century , 1900-1984.

1.3 THE TASK

It is therefore the ultimate task of the present study, in comparing the general tornado risk factor across the whole of Britain, to determine the intrinsic risk probability for certain well-populated coastal regions for which the data are the most complete. This will enable tentative conclusions to be drawn about the tornado risk factor in feebly populated places, with the Sizewell coast of Suffolk in particular, in mind.

The work involves utilising the large tornado data bank compiled and maintained by the Tornado and Storm Research Organisation, TORRO. The collection was begun, in a small way, by the author in 1966, whose first site study was that of the Oxford tornado of 16 October 1966 (8 prefabricated single-storey homes destroyed or irreparably damaged). After the author had spent five years in Canada data acquisition recommenced seriously in 1972, and increased dramatically with the founding of TORRO in 1974 and the pooling of records with Michael Rowe in 1975 who had independently been compiling tornado data too.

TORRO now has data on file for over 1500 incidents involving tornadoes and tornadic waterspouts for Britain and Ireland. In addition, there are several hundred cases of funnel clouds over land, wind-devils and fire-devils (which can also be terribly destructive of property), and waterspouts over British waters. Also included are data on some 200 tornado cases from France, Belgium and Holland, and tornado data and references for other West European countries, coded according to the international TORRO scale. In developing a complete tornado and waterspout climatology for Britain and British waters, it was considered advisable to monitor as fully as possible tornadic occurrences on the near continent as well.

The compilation of this data base, with its accompanying details (chapters 2 and 3), provides the unique means for evaluating the magnitude and extent of the incidence of damaging tornadoes in Britain (chapters 3 and 4). From this it proves possible to calculate the frequency of occurrence for stated levels of wind-force and hence evaluate the tornado-risk potential for general and particular regions (chapter 5). Examples of damage caused directly by tornado winds in Britain and secondary damage involving airborne missiles are provided in chapter 6.

1.4 SHORT HISTORY OF TORNADO STUDY IN BRITAIN

There was no organised study of tornadoes in Britain before the founding of TORRO in 1974. Over the centuries occasional reports of severe whirlwinds or tornadoes found their way into ecclesiastical chronicles, privately-printed pamphlets, parish registers, the early newspapers and the early scientific journals, but until G.J. Symons founded British Rainfall and Meteorological Magazine in the 1860's no one man could be said to have shown much real interest in tornadoes. (Accounts of Britain's earliest known tornadoes from Mediaeval times have been given by Rowe (1975 a, b) and Meaden (1975) ; Britton (1937) is a useful basic source for pre - A.D. 1450 tornado incidents). Symons, however, in pursuing his duties as a magazine editor, did put on to record the numerous tornado occurrences which were reported to him. He was also the first person to note a large autumnal outbreak of tornadoes in Britain (15 on 19 October 1870 - Symons 1870) and he gave a useful account of the worst tornado of his time (at Cowes on 28 September 1876). He also carried out a very careful site investigation into the Wiltshire tornado of 1 October 1899 shortly before his death (Symons 1900). Yet, apart from setting many interesting events into print, he did not do any tornado data analysis as such.

The first thoroughly scientific investigation of a severe tornado event was that of Billet (1914). This was the T7 tornado which killed three people when passing from south to north through Glamorgan, and later through Herefordshire, Staffordshire, Shropshire, and Cheshire, on 27 October 1913. The only other undertaking of a similar thoroughness in the next 40 years was Lamb's study of the east Midland tornadoes of 21 May 1950 (Lamb 1950, 1957). Besides these, many individual tornado studies can be found scattered through the twentieth century volumes of the Quarterly Journal of the Royal Meteorological Society, Meteorological Magazine, and Weather. In 1954 Brooks published a map of England showing 23 tornado tracks on it, and Lamb discussed British tornadoes briefly on the basis of 60 tornado events taken from issues of Meteorological Magazine 1868 - 1950 (Lamb 1950, 1957).

An important advance came when Lacy (1968) made use of a press-clipping subscription (paid for by the Building Research Establishment to collect data on wind-damaged buildings) to compile a list of 78 tornadoes for the four years 1963-1966. This work emphasised how frequent tornadoes can be in the winter half of the year - 60 out of 78 were winter tornadoes, with 13 each on 15 November 1966 and 1 December 1966. It was this success which encouraged the author, when TORRO was founded, to subscribe to a press-cutting service as well, as from 1974. Since October 1975 when the first issue of the Journal of Meteorology appeared, many dozens of tornado papers, analyses and reports have featured in its pages. Contributions and observer report forms have been received from all parts of the country. Monthly tornado reports have appeared since January 1982, and special articles have given details of all known British tornadoes for 1960-1969. Further articles will cover the intervening period 1970-1981 (in all, some 779 tornadoes are known for the 25-year period 1960-1984).

The history, aims and work of TORRO have been given recently (J. Meteorology, vol. 10, 182-185, 1985) on the occasion of TORRO'S first international conference on tornadoes, waterspouts and severe storms. The range of data held between its five divisions is summarised in Figure 2. The incorporation of the 60-year old

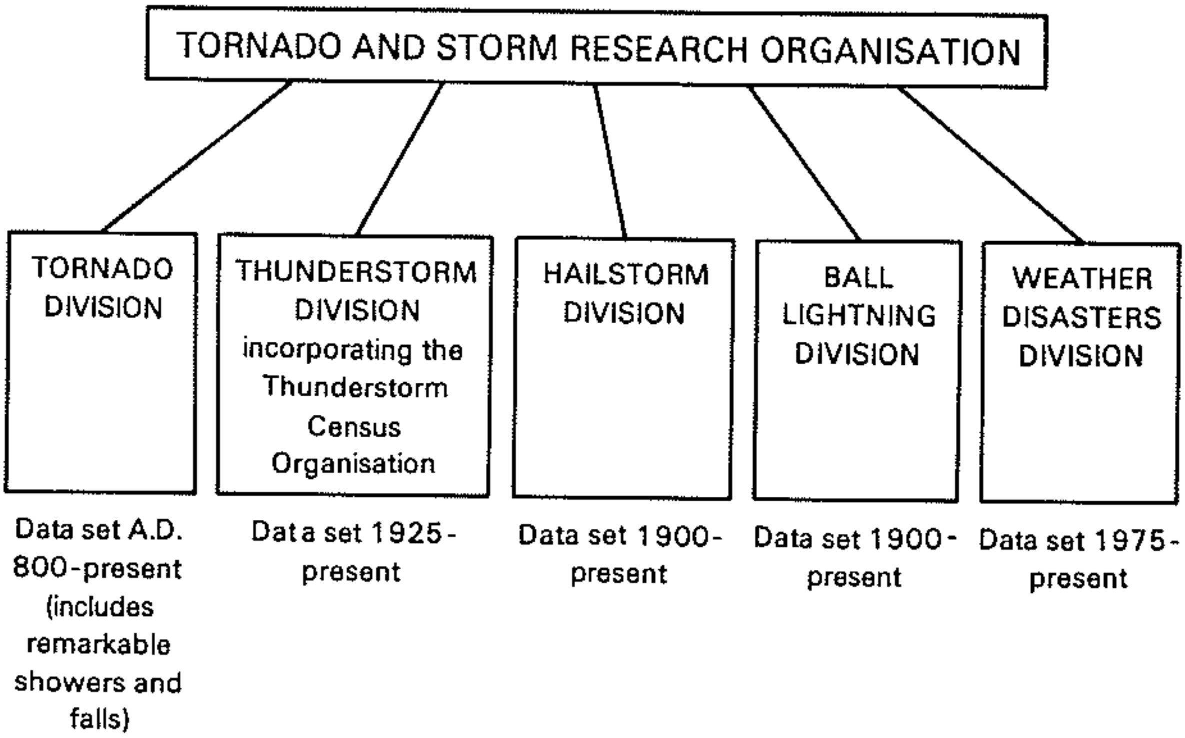

Figure 2

Thunderstorm Census Organisation into TORRO in 1984 brought with it the former's historic collection of thunderstorm press-cuttings which included limited but useful tornado information for the 1930s, 1940s and 1950s. Co-operation with Mr Philip Buller of the Building Research Establishment since about 1976 has been much valued. Mr Buller most kindly allowed us access to their tornado press-clippings which date back to November 1962. It is for these several reasons, involving the efforts of so many people , that TORRO has been able to develop the extensive data base which it now possesses.

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CHAPTER 2 - TORNADOES, AND THE BRITISH TORNADO DATA-BASE

2.1 TORNADOES AND WHIRLWINDS

In scientific and American usage, and increasingly in British popular usage, the word 'tornado' is used to signify that branch of the overall whirlwind genus which constitutes the major whirlwinds - the bad weather whirlwinds. This distinguishes them from the minor whirlwinds, examples of which are the so-called dust-devils, water-devils, fire-devils, etc.

All whirlwinds have one important property in common : that of an ascending current of warm air which rotates as a helical vortex and in which a quasi steady-state is maintained by the entrainment of a continuous supply of incoming buoyant air into the bottom of the vortex from all directions (Meaden 1985).

The minor whirlwinds or whirlwind devils usually develop from thermal plumes, induced by solar heating, which are set into rotation by some means. The gyratory motion starts or appears to start at ground level, and the vortex of rising warm air is sometimes rendered visible by the spiral raising of dust, sand, smoke, or light debris, etc. Because the weather is often sunny, these are called fair-weather whirlwinds. Even in Britain they can be powerful enough to overturn mobile-homes, tear roofs from sheds or pre-fabricated buildings, and project missiles in a wind-field whose speed can be several tens of m/s.

The major whirlwinds consist of tornadoes and tornadic waterspouts (tornadoes over large water-surfaces) and are referred to as such in the remainder of this report. In these cases, the ascending vortices of air can be extremely violent because they rise to a powerful cumulonimbus, or a towering or fast-growing cumulus, in which part of the immense updraught into the cloud has been set rotating by some means. Such rotation most typically commences inside the cloud, and the gyratory motion, although a continuously-rising one, paradoxically extends its influence progressively downwards towards ground (or water) level.

Very often the air is so humid and the gyrations so rapid that water vapour condenses within the vortex of reduced air pressure. This makes visible a funnel-shaped cloud of water droplets which descends within the rapidly-rotating and ascending helix. As long as the gyrating winds reach ground-level (whether or not a visible funnel of cloud droplets does as well), the whirlwind is termed a TORNADO - and in the case of a water surface a TORNADIC WATERSPOUT (the latter term thereby excludes from this study the inoffensive "fair-weather waterspout" whose origin gives it closer kinship to the fair-weather land-devil).

The complete family inter-relationships are set out in Figure 3. Meaden (1985) provides details .

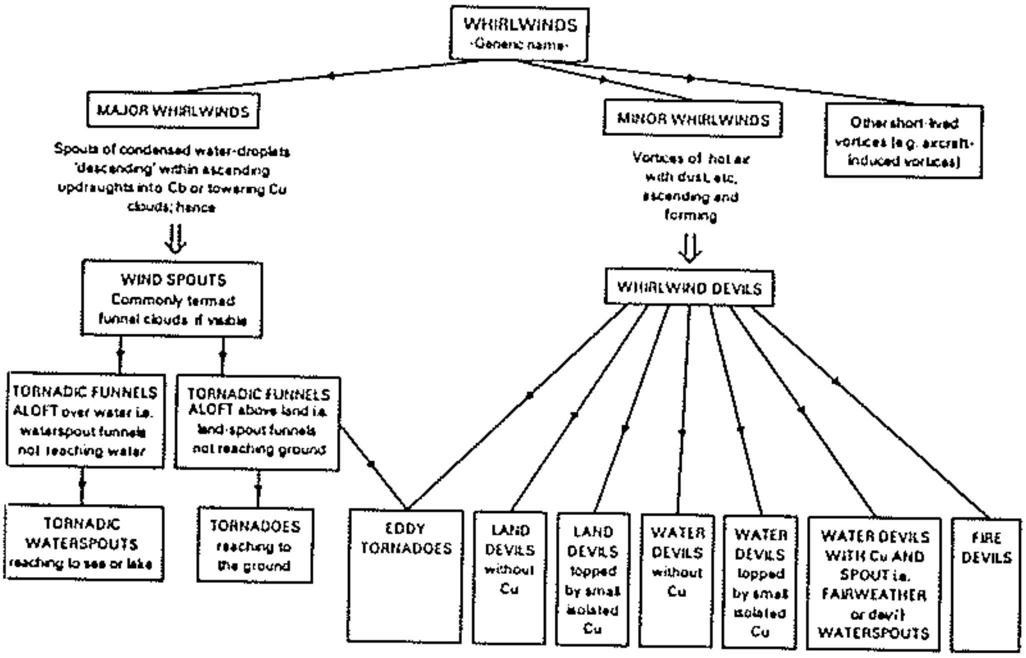


Figure 3

2.2 CYCLONIC VORTICITY AND THE FUNNEL CLOUD - THE TORNADO'S MOST CHARACTERISTIC FEATURES

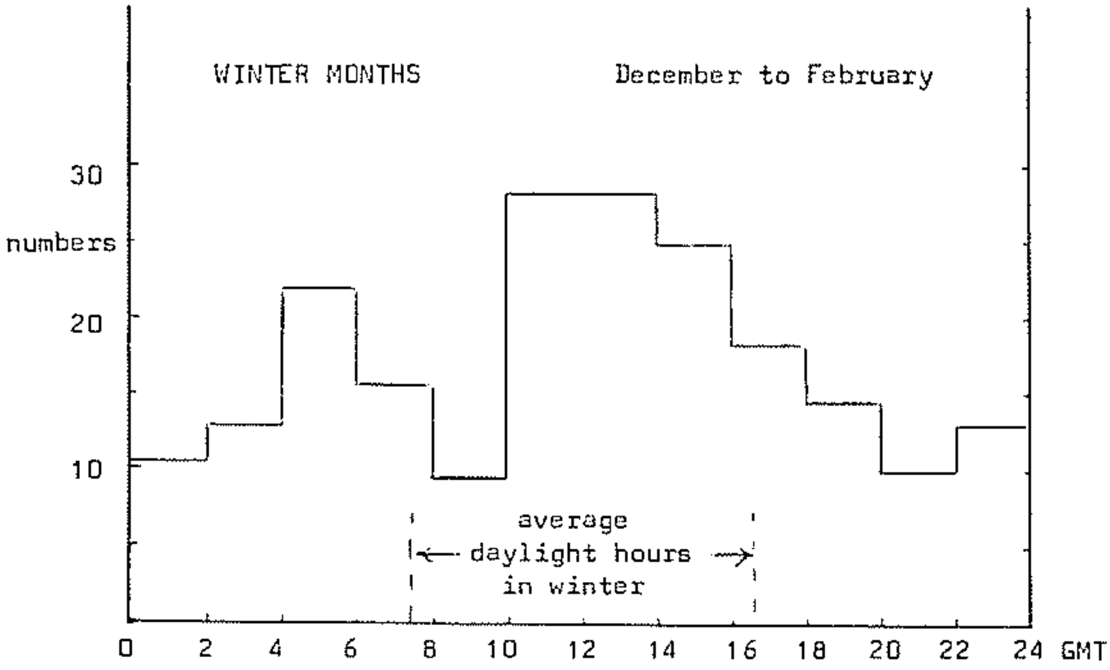
Tornadoes commonly develop from cumulo-nimbus clouds, either powerful isolated ones, as in severe local storms, or in connection with meso-cyclones or vigorous cold fronts. In the Northern Hemisphere these systems have inherent cyclonic vorticity which is the consequence ultimately of the earth's rotation. If a tornado develops, it too usually turns in the same cyclonic sense (i.e. anticlockwise).

Experiments using Döppler weather radar in recent years have shown that the tornado originates at the downdraught-updraught interface in the lower-middle levels inside the cumulonimbus. The incoming warm moist air is forced to turn as it ascends due to wind-shear (variation of wind speed with height) and the proximity of a persistent drier, cooler, downdraught. The initial cyclonic rotation has a large diameter and is weak. As the spiralling extends upwards and downwards, so the overall diameter diminishes and the speed of rotation increases (a conservation of angular momentum effect). This vortex-narrowing concentrates the energy , and raises the wind-speed briskly. Soon, potentially-damaging winds arrive at ground level. A visible funnel from cloud to ground is formed if the moisture of the air and the spin-rate are sufficiently high. Otherwise, a funnel of condensed water droplets may not arrive at the ground.

Other reasons why a funnel cloud might not be noticed, although destructive winds are at ground level are (a) poor visibility in the line of sight of the observer due to falling rain or hail combined with the lowness of other clouds and (b) night darkness. The work of TORRO has indicated that over half (56%) of Britain's known winter tornadoes (December to February) occur during the hours of darkness (as against 5 per cent of the summer ones - see Figure 4). It is the weaker tornadoes which are more likely to get missed in this way.

2.3 OTHER CHARACTERISTICS OF TORNADOES

Nevertheless, in the absence of a funnel cloud sighting, other attributes of a tornado may be evident from ground and damage inspection. It is important to state these, because suitable known combinations of these effects have allowed identification to be made unequivocally, even in the absence of direct eye-witness accounts. This is in any case the only means of counting night-time tornadoes, or of enumerating day-time ones which chanced to strike a region where there were no eye-witnesses. This list also provides the engineer with a commonplace description of the damage that a tornado can provoke : (a) shear effects : the twisting of tree trunks, branches or other matter by the intense shear wind-field.



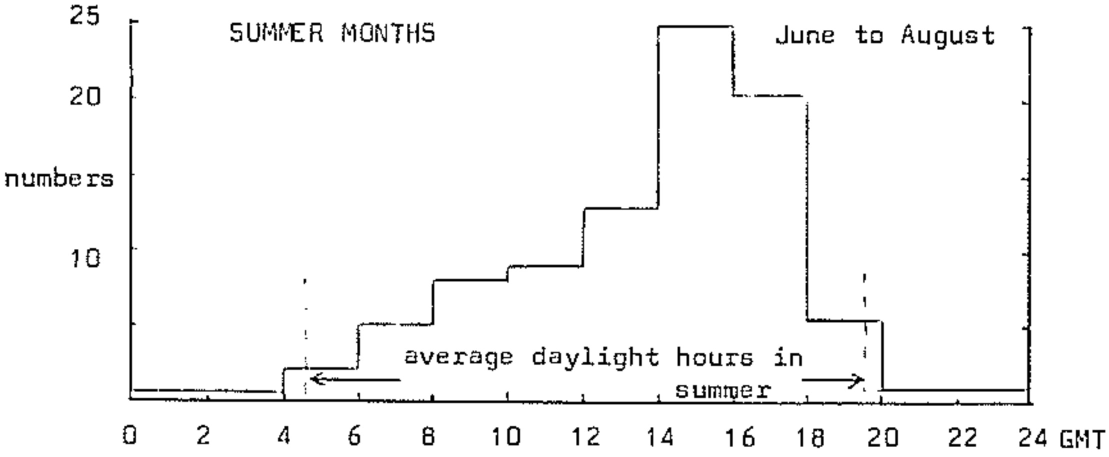


Figure 4. Comparison of the times of occurrence of tornadoes in the summer and the winter months, 1950 - 1984.

(b) suction effects : evidence of damage of an explosive nature, including windows and doors blown out, roofs sucked off, windows sucked from motor-vehicles, objects sucked through partly open windows, etc. Suction effects originate from the rapid pressure drop as the centre of the narrow core of the vortex is approached and reached. Effects are small for well-ventilated buildings.

(c) levitation effects, sheds, cars, debris, people, etc. raised into the air, the lighter objects turning in spirals,

(d) tremendous wind-pressure effects : thick trees snapped, uprooted, and often falling in different directions,

(e) the damage effects confined to a relatively narrow path-width. Along the track winds may reach or greatly exceed hurricane force, yet close by objects may be unharmed because winds remained light. Typical also is a skipping effect whereby objects apparently on the track remained untouched because the foot of the spout lifted off the ground for a short while. There may also be evidence of the transport of debris over unusually large distances, with some debris carried forwards and to the left of the main track. Important also is the secondary damage that airborne high-speed missiles can generate ; debarking of trees by impact of numerous small missiles is an uncommon but characteristic effect.

(f) deep furrows or narrow trenches gouged in soft earth or sand by the tornado. Sometimes such marks have a curvilinear or a curving shape, the result of a tornado skipping and tilting and causing a local suction spot, or the effect of subsidiary vortices spinning round the perimeter of the principal tornado vortex.

(g) reports that the damaging storm was accompanied by an unusually loud roar or screaming (this is quite typical ; the noise is often compared with that of a closely approaching express train or jet aircraft).

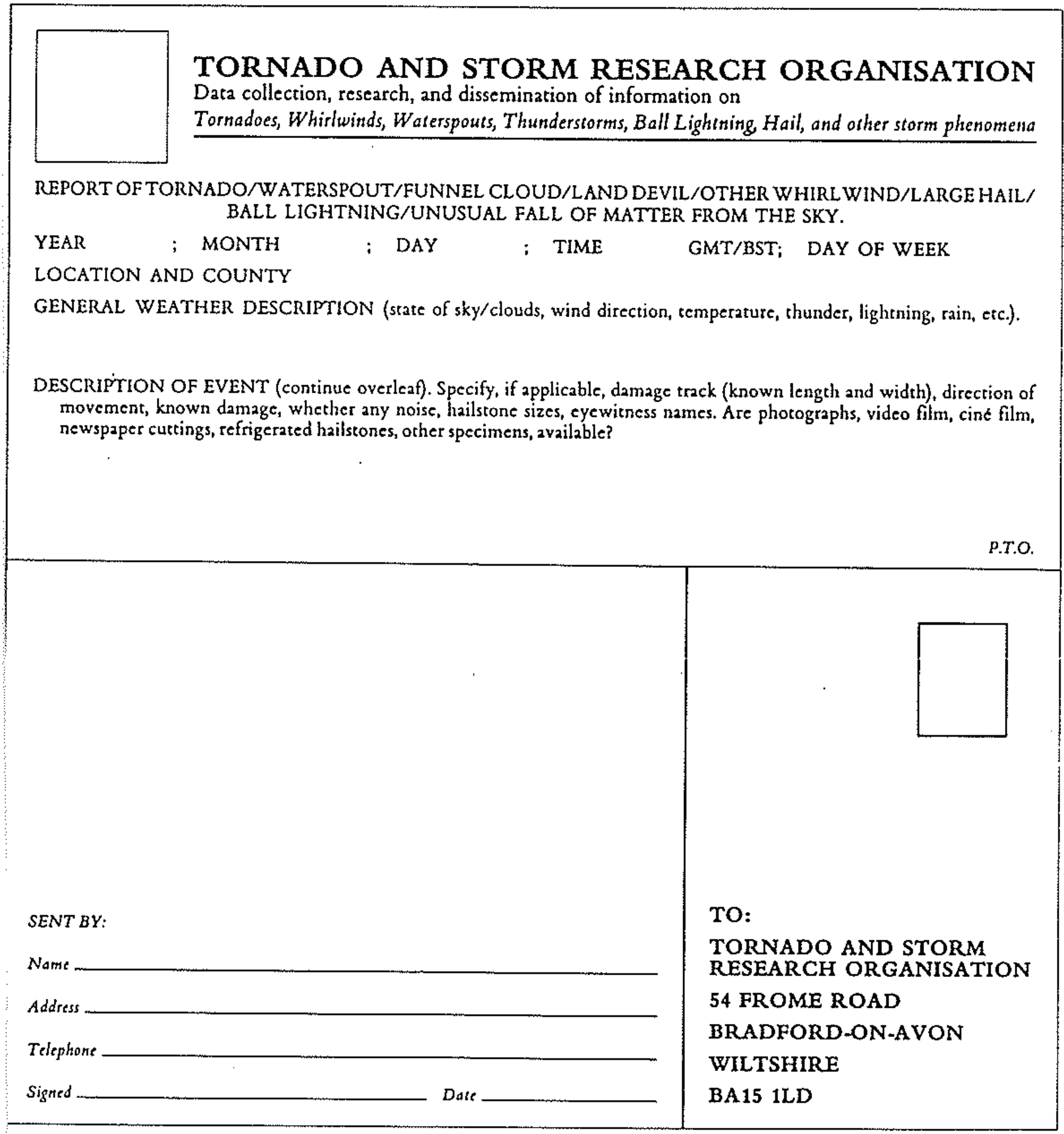
Some of the points indicated above are discussed in detail in later sections.

Windpressure effects, resulting from the vector addition of rotational and translational wind-pressure effects are the main object of this report and occupy much of its remainder. The possible consequences arising from rapid pressure drops or "suction" effects are considered in section 5.13, and the dangers posed by airborne missiles are treated in section 5.14.

2.4 THE PRIMARY TORNADO DATA-BASE

The basic store of information was put together by the author and Michael W. Rowe. Help came from the co-operating obervers and the press-cutting services of the Tornado and Storm Research Organisation, the other Directors of TORRO (D. Elsom , K. Mortimore, and A.J. Thomas), the readers of the Journal of Meteorology, Philip Buller and the press-cutting service of the Building Research Station (Garston), and others including particularly the late Michael Hunt, Senior Weather Forecaster of Anglia Television. British meteorological and scientific books and periodicals have been consulted. In addition, a newspaper appeal was initiated by M.W. Rowe in 1981, which is continuing. Tornado report cards are also issued to improve the efficient reporting of events to us (Figure 5). M.W. Rowe, Christopher Chatfield and the author have also undertaken a huge amount of archival research using the copyright libraries of Oxford, London, and elsewhere to take the tornado record back a thousand years. Several specialised newspaper-cutting collections have been consulted, besides also the records of the former Thunderstorm Census Organisation. In addition, there have been several dozen site investigations by the TORRO directors and members, and authors of papers to the Journal of Meteorology.

The result has been the documenting, in varying degrees of detail, of accounts of 1500 cases of tornadoes, about 200 cases of additional funnel-cloud sightings (without known surface tornadoes), and many hundreds of cases of waterspouts and waterspout-funnel clouds in British waters. Besides this, there are over a dozen reports of fire-devils and several hundred land- and water-devils. TORRO has a comprehensive collection of photographs and slides of tornado damage and of tornadoes in action.



TORNADO AND STORM RESEARCH ORGANISATION
Data collection, research, and dissemination of information on
Tornadoes, Whirlwinds, Waterspouts, Thunderstorms, Ball Lightning, Hail, and other storm phenomena

REPORT OF TORNADO/WATERSPOUT/FUNNEL CLOUD/LAND DEVIL/OTHER WHIRLWIND/LARGE HAIL/ BALL LIGHTNING/UNUSUAL FALL OF MATTER FROM THE SKY.

YEAR ; MONTH ; DAY ; TIME GMT/BST; DAY OF WEEK

LOCATION AND COUNTY

GENERAL WEATHER DESCRIPTION (state of sky/clouds, wind direction, temperature, thunder, lightning, rain, etc.).

DESCRIPTION OF EVENT (continue overleaf). Specify, if applicable, damage track (known length and width), direction of movement, known damage, whether any noise, hailstone sizes, eyewitness names. Are photographs, video film, ciné film, newspaper cuttings, refrigerated hailstones, other specimens, available?

P.T.O.

SENT BY:

Name ____

Address ______________________________________

Telephone _____________________________________

Signed ________________________ *Date* ____________

TO:

TORNADO AND STORM
RESEARCH ORGANISATION
54 FROME ROAD
BRADFORD-ON-AVON
WILTSHIRE
BA15 1LD

Figure 5. Obverse and reverse of the special storm-reporting postcards issued by TORRO.

The numerous and bulky files are indexed to provide a primary data-base of basic information. Each indexed item includes these details where possible ; type of whirlwind, year and date, day of the week, time, place, county, national grid reference(s), intensity on the TORRO scale, known path length, maximum path width, mean path width, and mean direction. As an example, the Oxford tornado of Sunday 16 October 1966, in which several buildings were demolished at Headington, a suburb of Oxford City, is cited thus : TN 1966 Oct 16 II/Sun/1605/Headington/Oxford/SP 554071-557080/T5/1.1 km/55 m(max)/35 m(av) / 200°(-020°).

This was the second known tornado (II) that day ; it started at 1605 GMT at N.G.R. SP 554071 and terminated at SP 557080 ; maximum known intensity, T5 ; known path length, 1.1 km ; maximum path width 55 m, average path width 35 m ; and it moved from SSW (to NNE). The day of the week is added as a cross-check to eliminate possible date errors. In all cases from 1960 onwards the *Daily Weather Report or Daily Weather Summary* has been consulted and the synoptic weather situation noted. In many cases the tornado can be related to a particular facet of the weather. Discussion of the intensity assessment (the T number) is deferred until the next chapter, at which place the full tornado specification (its T, L, W) will be explained (Section 3.6).

The maximum known path length is indicated where possible. Unless a very full site investigation has been made, the indicated path length will usually be shorter than the correct figure. It is not often that casual or chance observers look closely into the full details of damage path length and path width. Most observers are concerned with their neighbourhood. If fields are adjacent, the enquiry may end prematurely unless it happens that a nearby village (with another observer) lies on the same damage track. Sometimes a track can be followed for great distances, but then one cannot always be sure that the same funnel was continuously responsible, especially if the number of potential damage indicators is low and discontinuous. Each case must be taken on its merits. The main consideration must be the mean path width and the accumulated total ground path length for the tornado or sequence of tornadoes, whether or not ground contact was uniform. This should at least provide a minimum value for the total area damaged by tornadic winds from that storm. Sometimes the path width is well-attested over a certain damaged area, but the path length is not given. In some of these cases a minimum length of a kilometre is assumed. At any rate, the really important tornadoes, from the point of the present investigation, are the stronger ones (intensity T3 or higher). These have usually been rather better examined than have the weaker ones. The strong ones also tend to be the longer ones, and cover the greatest areas. T3 tornadoes bear mean wind-speeds above 46 m/s which exceed the instrumental English wind-speed records of around 43 m/s and comfortably exceed the 1 in 50 year gust-speeds used in conventional building design.

2.5 BRITISH TORNADO CLIMATOLOGY

For all dateable/timeable events from 1960 to 1984 the Daily Weather Report or the Daily Weather Summary of the Meteorological Office has been consulted. The weather systems causing the tornadoes have been identified in most cases. For all tornadoes from 1960 onwards, brief descriptions and references have been or are being published in the Journal of Meteorology (so far 1960-1969, and 1982 to the present have been published). Together with specific investigations of particular tornado events at irregular intervals over the years but particularly from 1950 onwards, it has proved possible to deduce that most British tornadoes form under the following circumstances (references to some of the published examples are also included) :

(1) isolated severe local storms, chiefly in spring and summer

Examples : 1958 September 5, Horsham (Sussex), references Rowsell 1960, Ludlam and Macklin 1960.

1967 June 13, Trowbridge - Melksham (Wiltshire), references Hardman 1968, and Meaden 1984.

(2) tornado cyclones, chiefly in spring and summer

Examples : 1950 May 21 East Midland Counties, references Lamb 1950 and 1957.

1979 June 24 Windsor (Berks) to King's Langley (Herts), references Buller 1979, Heighes 1979.

(3) thundery cells on cold fronts,

or on instability fronts in cool showery airstreams

– they can occur at any time of year, but are most frequent in autumn and winter.

Examples : 1978 January 3. Eastern England, Refs. Meaden 1978 and Buller 1978.

1982 September 21. England, refs. Elsom 1983, Meaden 1983.

1984 February 8. Wales and England, ref. Elsom 1984.

(4) thunderless line squalls

– they can occur at any time, but occur most frequently in autumn and winter

Examples : 1981 October 20. Southern England, ref. Turner, Elsom and Meaden 1986.

1981 November 23. Wales and England, references Kemp and Morris 1982, Rowe and Meaden 1985, Meaden and Rowe 1985.

(5) Other major sources of uplift and vorticity which lead to tornadoes include depression centres in a waving or triple-point situation.

Further recent papers with discussions on British tornado climatology are Elsom and Meaden (1984), Elsom (1985), Meaden (1985), Rowe (1985), Wright (1973), and Meaden (1976).

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CHAPTER 3 - TORNADO INTENSITIES, WIND-SPEEDS, PATH LENGTHS AND PATH WIDTHS

3.1 THE TORRO INTENSITY SCALE

It is important when investigating the damage wrought by a tornado to be able to relate the perceived damage to the corresponding local wind-speeds and forces that most likely caused the damage. Past anemometer records have been of little use for this purpose, because few of the world's anemometers have chanced to be in the path of a tornado's spirallingwinds, and the highest recording and/or survival speeds of the more common instruments are quite inadequate at around 50 m/sec.

The direct estimation of tornado wind-speeds is best achieved by studying the evidence of certain kinds of structural damage (to engineered structures, for example), or by analysing ciné-film or video-film sequences of entrained debris, the flight and impact of projected missiles, photographs of the shapes of funnel clouds, and so on. Good evidence like this is not often available, and is only gained gradually during many years of patient data accumulation. Hence, in order to facilitate a rapid understanding of tornadic strengths in day-to-day examples, and to permit meaningful intercomparisons to be readily drawn between them, the straightforward scale of intensities devised and perfected by TORRO has been used in the basic British/European tornado data bank.

The intensity numbers on this scale represent wind-speed bands apposite to their damage potential, and have a solid theoretical foundation which renders this truly international scale superior to others. The assignment of an intensity number simplifies discussion of a tornado's most significant attribute, its maximum known strength ; at the same time, it greatly aids information storage and retrieval. Of the many uses to which such knowledge can be put, the most important is certainly the statistical analysis of past incidents within a selected region in order to establish tornado-risk probabilities at different levels of intensity . This is the major purpose here.

The theoretical basis for the tornado intensity scale is the same as for the wind-speed formula of the modern Beaufort scale. Besides being the most natural formula to choose, nothing else offers all the advantages provided by the familiar Beaufort scale which sea-farers and meteorologists have trusted for so long. Sir Francis Beaufort proposed his original scale of wind-force for use at sea in 1805 ; the land version came later as did the formal wind-speed equation :

$v = 0.837\ B^{3/2}$ m/sec or $v = 1.870\ B^{3/2}$ mph ; or $v = 1.626\ B^{3/2}$ knots

where v is the wind speed at force number B.

For the TORRO tornado scale, tornado force zero is required at Beaufort force 8 ; this is gale-force, a speed that most structures withstand without damage. This condition is met by setting $B = 2(T + 4)$ where T is the tornado force number.

Therefore, $v = 2.367\ (T + 4)^{3/2}$ m/sec, or

$v = 5.288\ (T + 4)^{3/2}$ m.p.h., or $v = 4.598\ (T + 4)^{3/2}$ knots

The scale based on this formula has been tested in conjuction with Table 3.2 (p. 30, q.v.) for 13 years, firstly privately from 1972 and then within TORRO from 1974. It was announced at a meeting of the Royal Meteorological Society on 11 October 1975 and subsequently published (Meaden 1976). The simple relationship between TORRO tornado scale and Beaufort wind-force scale is given in Table 3.1 and Figure 6

TABLE 3.1

T	0	1	2	3	4	5	6	7	8	9	10
B	8	10	12	14	16	18	20	22	24	26	28

On both scales mean gale-force wind is identical at 18.9 m/sec (42.3 m.p.h.) for B = 8 or T = 0 ; also, mean hurricane speeds are identical at 34.8 m/sec (77.7 m.p.h.) for B = 12 or T = 2.

For computational purposes fractional values are sometimes needed, as, for example, Beaufort 9 = T 0.5, Beaufort 11 = T 1.5, etc. In rounded numbers T0 is the same as B8 and B9, T1 the same as B10 & B11, T2 the same as B12 and B13, etc. In fact, this

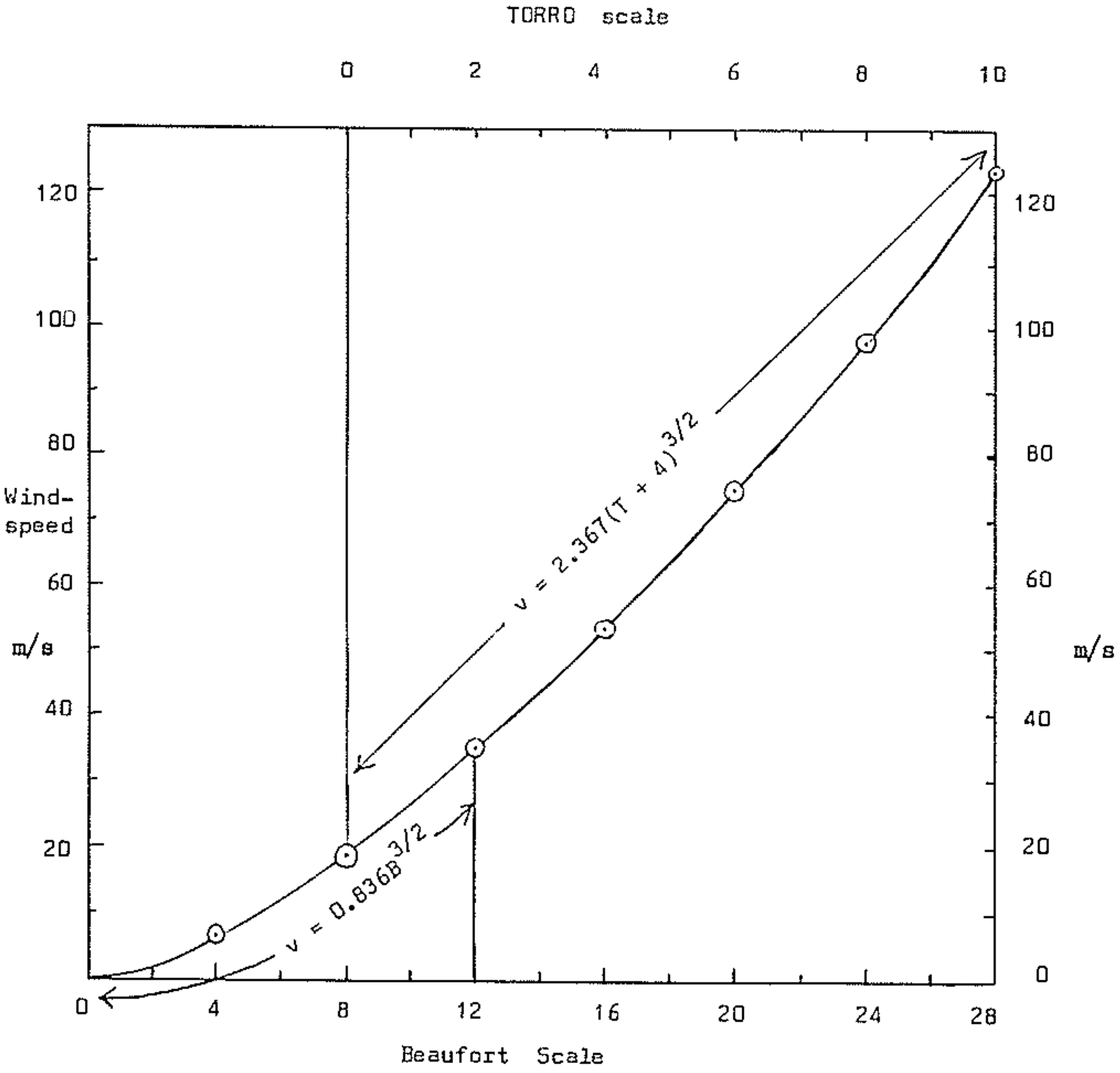

Figure 6. The universal 3/2 power curve for wind-speed which is common to the both the Beaufort and the TORRO scales, and is linked by $B = 2(T + 4)$.

convenient feature has the advantage of ensuring that the TORRO and Beaufort scales remain equivalent at all times, whatever transformations are made. For example, although B12 is hurricane force, the minimum acceptable hurricane-force wind-speed is strictly slightly above B = 11.5, which itself is 32.64 m/sec (72.9 m.p.h.). Because of the exact correspondance between the two scales this important speed is also the lower limit of the T2 band of wind-speeds.

In spanning ten numerical digits as it does, the TORRO scale has world-wide applicability. The worst U.S. tornadoes on record would be assessed as T10 ; the worst this century for Europe would be T9 or T10. The full TORRO intensity scale is set out in Table 3.2 (on p 30). Validation of the lower part of the scale (T0 - T2) is provided by the gale-hurricane part of the Beaufort scale. Furthermore, the damage for different intensities has a satisfactory cross-consistency with the damage-intensity relationships of the Fujita scale (Fujita 1973).

3.2 THE FUJITA INTENSITY SCALE

In the U.S. a scale proposed by T.T. Fujita has come into use (first published 1973). Fujita set his tornado force 1 (more precisely F 1.0) to equal minimum hurricane speed, i.e. he chose not Beaufort force 12.0 but what amounts to B11.53 instead. This oddity ensured there could be no exact equivalence between F and B scales. Moreover, he took his upper limit of F12 as being Mach 1 (at -3^{o}C), i.e. F 12 is 330 m/sec or 738 m.p.h. This high limit cramps the useable part of his scale, because the worst U.S. tornadoes only reach to F5 ; indeed, only 0.07% of recorded U.S. tornadoes have been known to reach the F5 level.

For conversion purposes we provide the following tables :

TABLE 3.3 Relation between the TORRO and Fujita Scales

T	0	1	2	3	4	5	6	7	8	9	10
F	0.1	0.6	1.1	1.6	2.2	2.7	3.2	3.7	4.2	4.8	5.3

F	0	1	2	3	4	5
T	-0.15	1.8	3.7	5.6	7.5_4	9.4_6

TABLE 3.2.

The International TORRO Tornado Intensity Scale

T0	LIGHT TORNADO 17-24 m/sec., 39-54 mph	Loose light litter raised from ground-level in spirals. Tents, marquees seriously disturbed; most exposed tiles, slates on roofs dislodged. Twigs snapped; trail visible through crops.
T1	MILD TORNADO 25-32 m/sec., 55-72 mph	Deckchairs, small plants, heavy litter made airborne; minor damage to sheds. More serious dislodging of tiles, slates, chimney pots. Wooden fences flattened. Slight damage to hedges and trees.
T2	MODERATE TORNADO 33-41 m/sec., 73-92 mph	Heavy mobile homes displaced, light caravans blown over, garden sheds destroyed, garage roofs torn away, much damage to tiled roofs and chimney stacks. General damage to trees, some big branches twisted or snapped off, small trees uprooted.
T3	STRONG TORNADO 42-51 m/sec., 93-114 mph	Mobile homes overturned/badly damaged; light caravans destroyed; garages, outbuildings destroyed; house roof timbers considerably exposed. Some of the bigger trees snapped or uprooted.
T4	SEVERE TORNADO 52-61 m/sec., 115-136 mph	Mobile homes destroyed; some sheds airborne for considerable distances; entire roofs removed from some houses or prefabricated buildings; roof timbers of stronger brick or stone houses completely exposed; possible collapse of gable ends. Numerous trees uprooted or snapped.
T5	INTENSE TORNADO 62-72 m/sec., 137-160 mph	Motor cars levitated; more serious building damage than for T4, yet housewalls usually remaining; the weakest, old buildings may collapse completely.
T6	MODERATELY-DEVASTATING TORNADO 73-83 m/sec., 161-186 mph	Heavy motor vehicles levitated; strong houses lose entire roofs and perhaps also a wall; more of the less-strong buildings collapse.
T7	STRONGLY-DEVASTATING TORNADO 84-95 m/sec., 187-212 mph	Frame house completely demolished; some walls of stone or brick houses beaten down or collapse; steel-framed warehouse-type buildings may buckle slightly. Locomotives thrown over. Noticeable de-barking of any standing trees by flying debris.
T8	SEVERELY-DEVASTATING TORNADO 96-107 m/sec., 213-240 mph	Frame houses and their contents dispersed over big distances; most other stone or brick houses irreparably damaged; steel-framed buildings buckled; motor cars hurled great distances.
T9	INTENSELY-DEVASTATING TORNADO 108-120 m/sec., 241-269 mph	Many steel-framed buildings badly damaged; locomotives or trains hurled some distances. Complete debarking of any standing tree-trunks.
T10	SUPER TORNADO 121-134 m/sec. or more, 270-299 mph or more	Entire frame houses and similar buildings lifted bodily from foundations and carried some distances. Steel-reinforced concrete buildings may be severely damaged.

For further information refer to *J. Meteorology*, vol.1, no.8, 242-251 and vol.8, no.79, 151-153.

TABLE 3.4. Relation between Beaufort and Fujita Scales

F	0.0	1.0	2.0	3.0	4.0	5.0	6.0
B	7.7	11.53	15.4	19.2	23.1	26.9	30.8

3.3 DURATION OF THE MAXIMUM WIND-SPEEDS

One must be able to relate the speeds given by the TORRO wind-speed formula to specific tornado events so that best estimates of the maximum forces can be determined. Tornado winds endure at a given place for times which are much briefer than those in general gales or widespread hurricanes. In contrast to gale-force gusts, gale-force winds are averaged over 10-minute intervals for synoptic and climatological usage. Peak tornado winds commonly last for much less than a minute, usually only a few seconds, which, in any case, can be sometimes long enough to cause very considerable destruction. A suitable definition is consequently one which recognises this brevity of action. Accordingly, we take the duration of wind to cause a specified kind or amount of damage as that of the fastest 400-metre run of wind at the point and height in question. This agrees with Fujita who used the fastest "quarter-mile wind". For a T 2 tornado this amounts to 10 seconds, a T 4 tornado 7 seconds, a T 6 tornado 5 seconds, and a T 8 tornado 4 seconds for the duration of the sustained maximum wind-speeds (refer again to the intensity scale in Table 3.2 on p. 30).

3.4 REFERENCE SET OF PHOTOGRAPHS

A set of typical photographs is provided in Figures 7-15 to illustrate the TORRO scale in use, and are best employed in close conjunction with Table 3.2 on p. 30. The full TORRO intensity scale provides for four distinct classes of destruction or devastation : (1) the motion of unattached moveable objects ranging from litter to caravans, cars and locomotives ;

(2) unanchored or lightly-fixed outbuildings such as sheds, verandahs, etc.

(3) buildings, ranging from minor roof damage to houses, to the destruction of steel-reinforced buildings

(4) growing plants, bushes, hedges, trees and forests.

Only class 3 has been used in the illustrative photographic set reproduced here to represent T1 to T9 tornadoes.

Figures 7-8 provide examples of T1 and T2 damage.

Figure 9 shows general T3 damage to all slopes of the roofs of a Newmarket, Suffolk, house caused by the tornado of 3 January 1978.

The T4 example (severe tornado) shows the complete removal of all tiles, battens and lining felt from a newly-roofed house in Rackenford, Devon on 10 January 1974 (Fig. 10).

The T5 example (Fig. 11) is that of the Oxfam warehouse in Bicester, Oxfordshire, severely damaged on 21 September 1982 (Elsom 1983).

T6 is represented in Fig. 12 by the destruction of a brick-built bakery at Linslade (Bucks) by the moderately-devastating tornado of 21 May 1950 (Lamb 1950).

A tornado on 8 December 1954 which followed a 20 km trail destroyed this factory at Acton in West London with T7 , strongly-devastating, winds (Fig. 13).

For a recent T8 example (Fig. 14) we reproduce a photograph from Léglise in Belgium (20 September 1982)(Goethuys 1983), while the T9 example (Fig. 15) comes from Ecourt in Northern France (24 June 1967)(Dessens 1984). Léglise and Ecourt are within 300 km of London.

Use has been made of the TORRO intensity scale in several dozen papers (principally in <u>J. Meteorology</u>), often with damage photographs showing all four classes of damage. It is important to realise the difficulty of attaining great precision with any scale of a type which depends upon assigning force intensities to non-engineered structures. Yet one has little choice because engineered structures are few in number. Existing buildings cover a wide range of types and represent all ages and possible exposures. Nevertheless, it is thought that with skilful site investigations of tornado-damaged structures it is usually possible to assign a correct T-scale intensity number to within ± 1, and thus establish the corresponding T-scale wind-speed with

Figure 7. The verge tiles removed from the gable ends of these houses together with more general damage to the roof of the middle house suggests T1 winds (25 January 1971, Welling, Greater London). Figure 8. Roof damage in Belfast, 26 September 1982, indicative of force T2 wind-speeds.