*The*
*JOURNAL of METEOROLOGY*

# TORNADO!

## Proceedings of the First Conference on Tornadoes, Waterspouts, Wind-Devils, and Severe Storm Phenomena

*OXFORD POLYTECHNIC*
*29th JUNE 1985*

# Whirlwind Phenomena

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# Proceedings of the First Conference on Tornadoes, Waterspouts, Wind-Devils, and Severe Storm Phenomena

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*CONFERENCE AND EXHIBITION*
*HELD AT THE OXFORD POLYTECHNIC, OXFORD*
*29th JUNE 1985*

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# CONFERENCE PROCEEDINGS

Chaired by Mr. Michael Hunt, of Anglia Television





# CONFERENCE EXHIBITION

The comprehensive severe local storms exhibition includes:

(1) the first display of TORRO's extensive photographic collection of British tornadoes, waterspouts, wind-devils and large hailstones and the damage that they have caused
(2) the first exhibition in Britain of tornado paintings and drawings by Leonard Silverman of Cambridge, Massachusetts
(3) the showing, twice, of the film *The Tornado*
(4) a display of slide sets and other teaching materials concerned with severe local storms
(5) demonstration of a disc-based educational package, including nearly 30 weather radar and satellite images, on a BBC micro computer by Dr. Andrew Eccleston of Malvern, Worcestershire.

# FOREWORD

It is with pleasure and satisfaction that the proceedings of this conference are published in association with the hundredth issue of the *Journal of Meteorology*. This has had the great advantage of permitting the proceedings to receive a world-wide distribution on a scale approaching 3,000, with only the limited drawback of unusual pagination for the alternative hard back version (for details of the two versions refer to page 247).

The conference, together with the published proceedings, has focussed world attention on aspects of the dangers posed by tornadoes and severe local storms in north-west Europe, especially in Britain. At the same time, research into tornadic and severe storm phenomena in Europe, and wind-devils and waterspouts as well, has evident implications for their understanding in other parts of the world too.

The second conference of the series is being planned to take place in two years time, again in Oxford. It is expected that topics will include the results of studies on the tornado threat in Britain, France, and other parts of Europe and elsewhere, the frequency and economics of damaging hailstorms and thunderstorms, ball lightning, and remarkable "falls" of unusual matter, besides other subjects thematic with whirlwinds and severe storms including one or two in the discipline of archaeometeorology.

*Frontispiece. Recent tornadoes in the British Isles.* The tornado in the top left photograph by Mr. Nick Coy shows the classic twisting column (Nass, Co. Kildare, autumn 1980); the other tornado photograph shows a well-developed wall cloud and funnel at Windsor, Berkshire, on 24th June 1979 (copyright Mr. J. W. F. Russell); the third photograph shows T5 tornado damage at a warehouse in Bicester, Oxfordshire, 21st September 1982; the last photograph shows tornado damage along a track up to 100 metres wide through a forest at Ablington, not far from Stonehenge, Wiltshire, 30th May 1979. Every tree has been snapped, twisted or uprooted; no buildings were in the tornado's path.

*A Message of Welcome from Professor H. H. Lamb*

# TORRO – AND THE IMPORTANCE OF INDEPENDENT METEOROLOGICAL RESEARCH

By HUBERT H. LAMB

*Emeritus Professor, Climatic Research Unit, University of East Anglia*

The first conference of TORRO (the Tornado and Storm Research Organisation, which has now been running for over ten years and has recently taken over the responsibility for continuing the work started between 1924 and 1931 by the Thunderstorm Census Organisation) is an occasion for warm congratulation and good wishes for the future. It is greatly to be hoped that what has so far been achieved by Dr. Meaden's enthusiasm with TORRO (and Morris Bower before him with the T.C.O.) will encourage further generations of observers to carry on the good work.

There has been a great and well-known tradition in these islands over more than three hundred years for scientific observations, particularly in the fields of weather and natural history, made and regularly maintained by unpaid volunteers. Some of the early ones were inventors and pioneers using the first meteorological instruments. Others also contributed valuably to our knowledge of past climate just by keeping weather diaries. No doubt, some of the pioneers hoped that their patient efforts would bring more understanding of the processes which produce our weather and climate than they themselves lived to see. Others were content to compile a record, in some cases maintained over many years, for later generations to interpret.

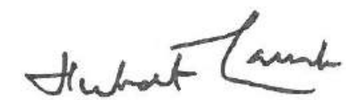
It is our good fortune that it is just in this century when atmospheric science has made such strides, particularly with the aid of new instruments such as the radio-sonde and satellite-borne sensors which enable us to see the global (and lesser-scale) processes whole and to keep a continuous watch, that many of those old manuscript records can be analysed and understood for the first time. But, for all the importance of modern technology, without those old observation records we would know much less than we now do about the climate of recent past centuries and about the course of changes working over time-scales of decades and centuries. And in the realm of studying meteorological events and processes on the scale of tornadoes and thunderstorms, from a few metres to several tens of kilometres, there is still much that keen human observation can contribute. For some purposes – another, not unrelated example is the small-scale wind patterns of sea breezes and convection over hills – there is no substitute for a close network of human observers.

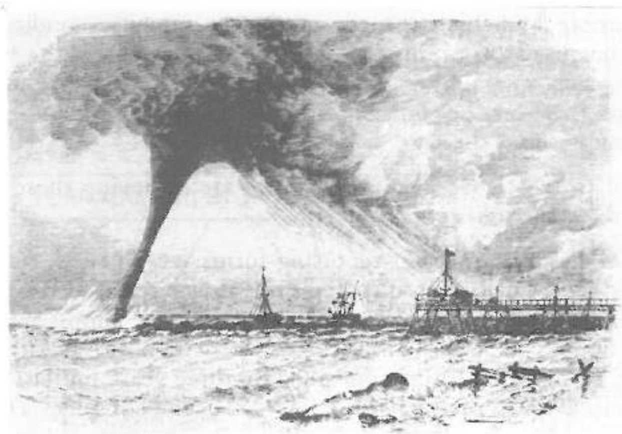
The history of such networks is, of course, not confined to the British Isles. A similar inspiration produced weather records on a daily basis arranged in Italy by the Accademia del Cimento in Florence from 1654 to 1670, and another network covering central Europe with daily weather observations was centred on Breslau (now known as Wroclav) in the early 1700s. The old meteorological society of the Palatinate of the Rhine produced volumes of three-times daily meteorological observations at a network of places covering Europe and beyond printed in year books from 1781 to 1792. Those efforts have made it possible to analyse the hot summer of 1783, the severe winters of 1784 and 1785, and some North Sea gales in 1717 and 1792 that seem to have somewhat exceeded the severity of more recent storms that have swept the same area. In this century, the close distribution of meteorological observers organised by Professor V. Bjerknes in (neutral) Norway during the First World War led to the first clear identification of fronts: a concept that revolutionised synoptic meteorology. Later still, Tor Bergeron, who had once been a young associate of Bjerknes, organised a dense network of rainfall observations in his "Pluvius" project in central Sweden, which revealed the astonishing effectiveness of quite small-scale hill-and-dale topography in terms of the rain and snow, and associated cloudiness, measured over the terrain.



All these investigations – but none more than the investigation of tornadoes, hailstorms and severe thunderstorms – concern phenomena that cause great economic losses and damage to life and property. And they have all produced valuable contributions to knowledge and understanding at remarkably little outlay cost.

Sad to say, such efforts seem rarely to be appreciated by the well-funded establishment groups until at least one generation later! Happily, however, collaboration in such exploits brings its own kinds of rewards. My congratulations and best wishes to you all.





Waterspout off Worthing on the south coast of England, 21st August 1864. Two accounts were published in *The Times,* two days later. The contemporary engraving was reproduced in the *Sussex County Magazine* in 1938 (vol.12, p.763) with the following particulars: The morning was dull and thundery with severe lightning and the sea was calm with a light breeze from the N.E. Shortly after 9 a.m. the clouds began to revolve in a circle, some half-mile in diameter, which descended until when some 50 feet above the sea it increased and united with a dense vapour raising from the water in the shape of a cone. At the same time the sea became rough, great waves rolling to a centre and throwing up masses of foam. Ten minutes later the waterspout broke and was followed by a storm of hail. The disturbed water flowed rapidly eastwards and when opposite Brighton another waterspout was formed.

# TORRO, THE TORNADO AND STORM RESEARCH ORGANISATION

## The main objectives and scope of the network

By G. TERENCE MEADEN

### *PART A.* ITS FORMATION AND EXPANSION

TORRO was formed in 1974 when I came to realise that only by means of a nationwide organisation specifically set up for the purpose would it be possible to determine with acceptable accuracy the great extent to which Britain suffers from tornado damage every year.

For many years I had been amassing data on my own, and had carried out several disaster-site surveys. These early investigations (TN 1966 October 16th, Oxford, five houses destroyed beyond repair; TN 1967 June 13th Trowbridge/Melksham, cricket pavilion with 50 people in it lifted off the ground) and eye-witness descriptions of these and other cases showed me how important individual events could be to public life and property. Also, by 1974 my file on British tornadoes was bulging with nearly 750 events, and it was beginning to appear that perhaps 30-40 documentable tornadoes annually might be added in ensuing years if enough people were involved in the task. By this means, it was hoped to assemble for Britain future tornado data with minimal omissions, and to analyse and publish the data for the public good. Thus the aim was to determine with as high an accuracy as possible (1) the distribution and severity of British tornadoes, past and present, (2) the conditions of their development, so that, ultimately, forecasting guidelines might be feasible by which tornado-producing synoptic conditions could be efficiently recognised, (3) estimation of return periods so that the future tornado risk at any place may be established, and (4) to demolish the text-book misconception that tornadoes occur infrequently in Britain, and hence create a public awareness about the true dangers that do exist.

The extent to which we have achieved or are achieving these aims is being demonstrated today at this conference.

So, in 1974 the first tornado reporting-forms were issued, the first reports produced, and the TORRO intensity scale privately circulated. The intensity part of the full scale, based on Beaufort, was devised in 1972, almost two years before hearing of Fujita's Japanese-American scale which he published in 1973 (*Weatherwise, 26,* 56-62). Testing continued for three years, until its publication at a conference in 1975 (*J. Meteorology, 1,* 242-251). The complete TORRO scales, with TLW formulae, are reproduced in Table 1. The metric, open scales, well-suited for international use, are designed for the weaker tornadoes of the non-American world.

Early in 1975 I had the good fortune to discover that Mike Rowe had also been compiling tornado reports for some years. Parts of our collections overlapped, for example with regard to much of the historical search 800 A.D. to 1800 A.D., using Britton's *Chronology, Phil. Trans. Royal Society,* and *Gentleman's Magazine.* In several other aspects the collection dove-tailed usefully. I should add that, besides



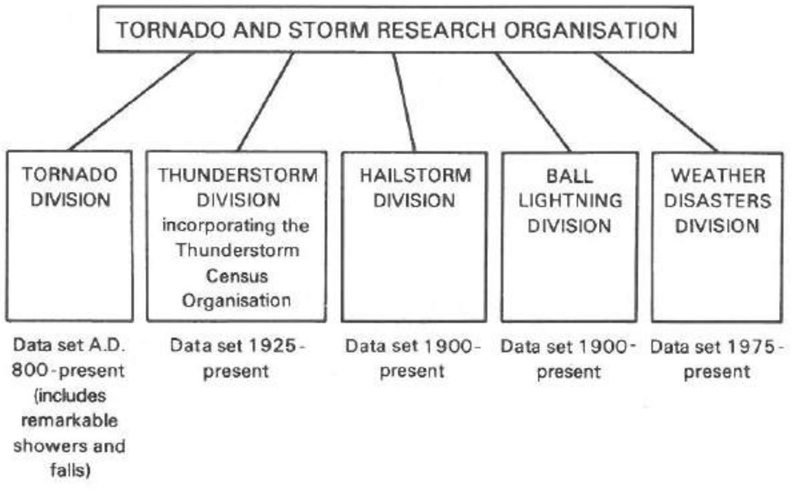
Table 1: The International TORRO Scale for tornado intensities based on wind speed (intensity T), path length (scale indicator L), mean path width (scale indicator W), and path area (scale indicator A).

| *TORRO Scale Number* | *WIND SPEED v (intensity T)* | *PATH LENGTH l (scale indicator L)* | *PATH WIDTH w (scale indicator W)* | *PATH AREA a (scale indicator A)* |
|---|---|---|---|---|
| 0 | 17-24 m/s | up to 215m | up to 2.1m | up to 464sq.m. |
| 1 | 25-32 | 216-464m | 2.2-4.6m | 465-2150sq.m. |
| 2 | 33-41 | 465-999m | 4.7-9.9m | 2160-9990sq.m. |
| 3 | 42-51 | 1.0-2.1km | 10-21m | 0.01-0.046sq.km. |
| 4 | 52-61 | 2.2-4.6km | 22-46m | 0.047-0.21sq.km. |
| 5 | 62-72 | 4.7-9.9km | 47-99m | 0.22-0.99sq.km. |
| 6 | 73-83 | 10-21km | 100-215m | 1.0-4.6sq.km. |
| 7 | 84-95 | 22-46km | 216-464m | 4.7-21sq.km. |
| 8 | 96-107 | 47-99km | 465-999m | 22-99sq.km. |
| 9 | 108-120 | 100-215km | 1.0-2.1km | 100-464sq.km. |
| 10 | 121-134 or more | 216-464km or more | 2.2-4.6km or more | 465sq.km. or more |

*Basic formulae:* $v = 2.367\ (T + 4)^{3/2}$ m/s, where T is the TORRO force number; the path length indicator $L = 3 + 3 \log l$, where l is in km and the logarithm is to the base 10; the path width indicator $W = 9 + 3 \log w$, where the mean path width is in km; and $a = lw$. The set (T, L, W) is used to specify tornado strength characteristics of known damaging tornadoes and of potentially damaging tornadoes.

tornadoes, we had both been compiling data on waterspouts and other whirlwinds, hailstorms, ball lightning, and remarkable falls of unusual matter from the sky. There is likely to be a place for all these subjects at future conferences.

The launching of *The Journal of Meteorology* in October 1975 provided a great impetus for TORRO at just the right moment. It put us rapidly in touch with an expanding group of collaborators and provided an effective publishing medium for the monthly and occasional reports of TORRO. And so it was in 1975, also, Bob Prichard suggested that TORRO should cover conventional thunderstorm reporting too, with reports published monthly. Since 1977, this division has been



run by Keith Mortimore, and since 1984 the 60-year old Thunderstorm Census Organisation (founded by Mr. S. Morris Bower) has joined us too (see Fig.1), illustrating the structure of the organisation.

A *hailstorm* division was also begun in 1975 (cf *J. Meteorology, 1,* 25, 260, 313). A lot of data is on file, and one series of storms has been thoroughly investigated (5th June 1983). We even have specimens from such storms "on file" in a freezer. Since 1984 this division has taken off anew under the excellent direction of Dr. Derek Elsom. Derek joined TORRO in 1980 and has contributed extensively to TORRO's research studies and site investigations on tornadoes.

*Ball lightning* has always been of particular interest to us. Several dozen reports have been collected, direct from eye-witnesses, especially through the enthusiasm of Mike Rowe, and a lot of accounts published. This year Mark Stenhoff has joined us. He has spent over ten years in ball lightning study, and has conducted several investigations into particular incidents. His own files included over a hundred known ball lightning cases for Britain.

Next, there is the unusual subject of *remarkable showers* or *falls* which offers considerable scope for site investigations and the analysis of hard evidence. The difficulty usually lies in the supposed circumstances of the fall. Many case-histories are on file, but the only one which is definitely 'cast-iron' in the sense of being a tornado-related fall from a cumulonimbus is the Bournemouth coke-fall of 5th June 1983. In addition, the fall of shells at Dilhorne on 21st March 1983 (Paul J. Swinhoe, *J. Meteorology, 8,* 233-238) appears likely to have been tornado-related, although the causative 'bag of shells' which fell and dispersed may not necessarily have been carried to a really great height.

Next, I must mention Mr. Albert Thomas whose speciality interest is weather disasters. This year he will be completing ten years of his monthly bulletins of world weather disasters and his annual bulletin of British weather-related deaths.

I now return to the Tornado Division, in connection with which I must acknowledge the cooperation provided by Philip Buller of the Building Research Establishment at Garston, Watford, and Michael Hunt, Senior Forecaster of Anglia Television. Both have passed on to us every scrap of tornado data that ever came their way, and on at least a couple of occasions (1st December 1975, 23rd November 1981) Michael Hunt made very helpful appeals on local television for specific tornado information. We are all of the opinion that, if this could be done regularly on national television, Britain's current tornado rate would be likely to increase by five times or more.

Finally, I must mention that in 1974 TORRO also established a European tornado data bank which now holds a few hundred non-British cases. It is proposed that TORRO could in future act as a clearing house for all known European tornado events.

The work of three of the principal divisions of TORRO will now be briefly presented, starting with the Tornado Division discussed by Michael Rowe.



## The International TORRO Tornado Intensity Scale

| | | |
|---|---|---|
| T0 | LIGHT TORNADO<br>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<br>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<br>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<br>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<br>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<br>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<br>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<br>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<br>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<br>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<br>121-134 m/sec. or more,<br>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.

*Part B.*

## THE WORK OF THE TORNADO DIVISION OF TORRO

By MICHAEL W. ROWE

The most important work of TORRO to date has been the building up of its large data bank of British tornado cases. For the period before 1450 our sources were the numerous medieval chronicles. From 1665 onwards the *Philosophical Transactions* of the Royal Society contain some useful accounts, and when these peter out in the mid-18th century the *Gentleman's Magazine* (from 1731) and the *Annual Register* (from 1758) become the main sources of data. These in turn become less useful during the mid-19th century, but tornado documentation improves greatly after about 1860 with the establishment of meteorological journals such as *British Rainfall, Meteorological Magazine* and the *Quarterly Journal of the Royal Meteorological Society*. For various reasons, tornado reporting in these publications declines after about 1920, but *Weather* (especially from 1946 to 1971) has published some useful accounts. We have also consulted innumerable minor sources.

Since 1963, our main source of tornado reports has been press cutting services, and the number of known British tornadoes rises dramatically from that year onwards. The foundation of TORRO in 1974, and the *Journal of Meteorology* in 1975, has further increased the number of reports we receive; TORRO is most grateful to readers of the *Journal of Meteorology*, and others, who have helped our work over the past ten years. Finally, TORRO has placed appeals for information in hundreds of local newspapers, and this has revealed a considerable number of previously unknown tornadoes (and other whirlwinds), most usefully from the pre-1963 period when no press cutting service was in use. Occasional appeals have been made on local radio, and Michael Hunt, while senior forecaster for Anglia Television, made several useful appeals to viewers in eastern England.

Current work is still largely concerned with the time-consuming task of making tornado documentation as complete as possible. The results of research on recent tornadoes is published as a monthly report in the *Journal of Meteorology*; the first such report was for January 1982. The period 1960-1981 will eventually be covered by a series of annual reports, of which those for 1960-1969 have already appeared. More detailed analyses of important cases are frequently published [e.g. Meaden (1983); Elsom (1983)].

TORRO has always realised the importance of investigating the damage tracks of tornadoes, and a number of such site investigations have been carried out, both by TORRO members and by readers of the *Journal of Meteorology*. It is to be hoped that much more fieldwork of this nature will be carried out in the future.

With the comparatively large data bank which TORRO now possesses (on 1500 tornadoes and several hundred waterspouts, wind devils, etc., for Britain), it is possible to investigate the distribution of British tornadoes in time and space in some detail. The best recent summary of progress in this field is by Elsom and Meaden (1984). Highly important, also, is research into the meteorological situations in which tornadoes form, so that in time it may be possible to forecast their occurrence. Because data collection is so time-consuming, we have not yet been able to devote as much attention to these more general matters as they deserve. One major task, however, is now under way: the preparation of a comprehensive catalogue of all known British whirlwinds.



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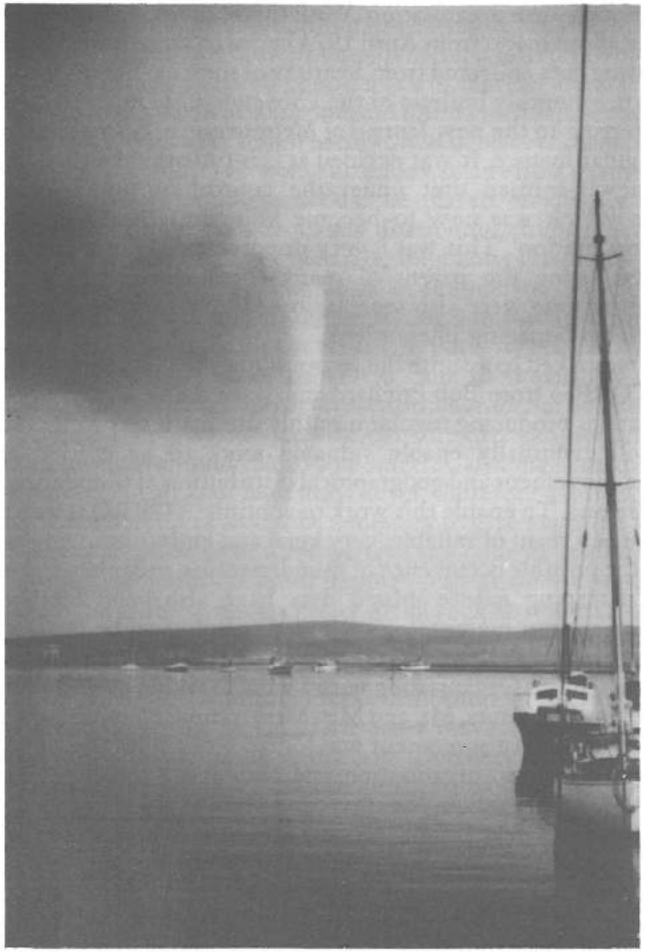

Fig.1: Waterspout crossing the Solent from near Keyhaven to Colwell Bay on the Isle of Wight on 6th July 1966. Some T1 damage resulted. This was a rare southward moving tornadic waterspout. (Photographed by Mrs. Olive Thomas).

*Part C.*

## THE WORK OF THE THUNDERSTORM DIVISION OF TORRO

By KEITH O. MORTIMORE

Prior to the formation of the 'Tornado Research Organisation' in 1974 the collection of thunderstorm data and reports of damage attributed to thunderstorm-related phenomena was carried out on a national basis solely by the 'Thunderstorm Census Organisation' at Oakes, Huddersfield, and the 'Electrical Research Organisation' at Leatherhead, Surrey. In March 1974 the E.R.A. withdrew from the scene and with the TCO only publishing a very brief summary, and that around two years in arrears, there was an urgent requirement for a new thunderstorm organisation. With this in mind, Bob Prichard, decided to do something about it and from April 1974 began to write monthly thunderstorm summaries using data collected from a variety of sources. These early reports were published in the monthly bulletin of the *Climatological Observers Link* for a while before transferring to the new *Journal of Meteorology* in 1975 where they were to become a regular feature. It was decided at this time to take the logical step and bring this newly-formed unit under the control of the Tornado Research Organisation which was now to become known as the 'Tornado and Storm Research Organisation'. This was a very important development, because, with thunderstorms being the parent of many tornadoes and falls of large hail, thunderstorm reports were also seen as an additional source of information for these potentially-damaging phenomena.

In 1977 I was asked to assume the responsibility for running the thunderstorm division of TORRO from Bob Prichard and, since doing so, I have continued the interesting task of producing regular monthly summaries, as well as accumulating data that will eventually enable valuable work to be carried out into the development, movement and geographical distribution of thunderstorms in Great Britain and Ireland. To enable this work to continue TORRO is fortunate to have the assistance of a team of reliable, very keen and enthusiastic observers who are ever alert to the possible occurrence of thunderstorms, and related phenomena of a severe and damaging nature. Much data have also been forthcoming from publications of various meteorological and climatological bodies in this country.

In August 1984 TORRO was approached by a representative of the Thunderstorm Census Organisation with a view to taking over the running of that body, the previous directors, Mr. and Mrs. Morris Bower having sadly passed away two years previously. An agreement was forthcoming with the exciting prospect of rebuilding an historic organisation and combining forces to make the new TORRO/TCO combination the principal thunderstorm reporting and data collection source in Great Britain. Recent access to TCO records, which extend back to 1924, has revealed much useful information and brought to light additional reports of tornadoes and waterspouts, etc., together with incidents of large and damaging hail that hitherto had not been published. So far only a few years have been investigated and it is hoped that eventually many more occurrences will be added to TORRO files.

If thunderstorm data are to be of maximum practical use, it is necessary to put together a reliable reporting network that is well distributed and able to give



adequate coverage in those parts of the country that for so long have been badly represented, such as the more rural and mountainous areas, particularly in south-west England, mid and north Wales, Scotland, and the islands around our western and northern shores where winter storms so frequently go unreported. Publicity given to thunderstorm reporting in last December's *Journal of Metoerology* was so successful that new observers have been recruited in all parts of Great Britain and Ireland, including some of the more remote areas of north and west Scotland. This surge of renewed interest is most encouraging and it is hoped that our improved coverage will produce the results which we are seeking.

In the future there are a number of issues that will have to receive attention, but one in particular is worth mentioning. With the majority of observers finding it difficult to 'thunder-watch' throughout the full 24-hours because of the necessity to sleep, or through the nature of their employment, a different approach would seem to be called for when assessing period totals of thunder-days. It is frequently noticed that thunder-day totals at some stations differ considerably over very short distances and lead to anomalously high or low totals in places. Similarly, high totals can occur in areas of high observer concentrations. In an effort to smooth out such differences perhaps more emphasis should be placed on district totals where between a number of observers, adequately distributed, thunder activity may be assessed on a county basis, or, more sensibly, on a basis related to geographical features. This would tend to highlight 'areas' of thunderstorm development and reduce, somewhat, the possibility of dubiously high or low totals from adjacent individual observers, and also cover for missing reports where, perhaps, observers are not aware of a distant storm or are absent from their station.

The term, 'adequate coverage' has been used on a number of occasions, but what really does it mean? The greatest distance that thunder can normally be heard, given good conditions, is around 15 or 16 kilometres, although this distance can be considerably reduced in areas of high noise-level; therefore a distance of 30 to 35 kilometres between observers would be necessary to give anything like adequate coverage. This may be possible in some parts of the country but the prospects of achieving this observer density in lesser populated areas are not good. In an effort to partially offset this problem it is necessary to fall back on reports from 'travelling observers' and the media, the latter rarely being useful unless storms are particularly severe or damaging.

The present system for assessing days with thunder heard is beset with difficulties of a similar nature to those for other non-instrumental observations such as 'days with snow falling'; observer alertness can make substantial differences to totals at adjacent stations. Other systems have been tried or suggested, such as 'days with overhead thunder' or 'days with thunder of a sufficient loudness to be heard by the average observer going about his or her normal business. Bob Prichard discusses aspects of this problem in his own paper at this conference. Certainly, there is no easy answer to this problem and one can do no more than try to find a system that will give a more accurate picture of thunder distribution where less emphasis is placed on any one particular observer. As things stand at the moment, while using the present system, we can only ask our observers to be as vigilant as possible and to report the occurrence of storms outside their immediate area in the hope that a more accurate picture may be the result.

*Part D.*

## THE WORK OF THE HAILSTORM DIVISION OF TORRO

By DEREK M. ELSOM

The Hailstorm Division was established in 1975 in order to investigate and chronicle the occurrences, characteristics, intensities, effects and costs of British and continental European damaging hailstorms. Hailstones exceeding a diameter of approximately 10mm may cause considerable damage to vegetation (cereals, fruitcrops, market garden crops), greenhouses, conservatories, windows, perspex- and asbestos-roofed buildings, and the bodywork of vehicles and aircraft. An example of a recent British hailstorm was that of the Somerset hailstorm of 3rd October 1984 during which hailstones up to 38mm fell on the Somerset College of Agriculture and Horticulture, Cannington, causing £5,000 worth of damage to their apple crop in just 3-4 minutes. Greenhouses suffered damage too but the experience at Cannington points to lessons that can be learned to reduce future damage from hail. No breakages to panes of glass occurred in greenhouses where glazing of the butt-joints with silicone sealing was used, in contrast to greenhouses employing the conventional system of overlapping panes. Hailstorms on the continent may be of much greater severity as exemplified by the violent hailstorms of 11th-13th July 1984 which swept across France, East and West Germany, Austria, Czechoslovakia and Yugoslavia. Even so, these hailstorms provided some lessons which can be learned to reduce the potential damage from intense hailstorms. At Munich, hailstones ranging in size from pigeon's eggs to tennis balls caused damage totalling Dm 1.8 billion (£0.5 billion). At Munich airport, 400 cars were damaged along with 126 light aircraft and 22 passenger jets. The damage to the bodywork of vehicles and light aircraft was so severe that many became insurance write-offs. Over 300 inhabitants were injured, some very seriously, and at least three people died from heart attacks suffered during the storm. A warning of only an hour could have dramatically reduced the injuries to the inhabitants and the damage to vehicles and aircraft caused by the force of hailstones up to 75mm in diameter. People could have taken shelter, and aircraft could have been moved into hangers or have been diverted from landing at Munich Airport. Very short-term forecasting or nowcasting as developed in Britain using the radar-satellite FRONTIERS system offers the possibility of such a warning. However, at present this system interprets radar reflectivities only in terms of rainfall rates, rather than hailfall rates so its use as a warning system for damaging hail remains to be explored.

It is clear from TORRO documentation since 1975 that the annual frequency of damaging hailstorms in Britain is much higher than suggested by research undertaken by Rowsell (1956). Typically, large and giant hail affects only a few square kilometres; such a limited spatial extent, along with a storm duration of only a few minutes, means that many falls of large and giant hail go unreported or are reported only in local newspapers. Further, even in newspaper reports prominence may be given to intense flooding caused by a storm whereas the associated large and giant hail, being more localised in its effects, receives only brief mention. Provisionally, the use of the press-clipping services together with reports from TORRO (and Thunderstorm Census Organisation) observers points



to annual frequencies of between 5-10 days of damaging hail in England and Wales. In the next few years TORRO will analyse the regional and seasonal distributions of damaging hail.

For each incident of damaging hail TORRO documents the meteorological and synoptic conditions causing the severe hailstorm(s). An example of a recent analysis is that of the south coast of England hailstorms of 5th June 1983 undertaken by Mortimore and Rowe (1984) which complements analyses by Wells (1983) and Hill (1984). Of particular interest to TORRO are those hailstorms of the super-cell type because such storms, characterised by marked wind-shear and strong updraughts, may produce both damaging hail and tornadoes (or waterspouts). Well-documented examples of such storms include the Wokingham storm of 9th July 1959 (Browning and Ludlam, 1962), the Melksham-Trowbridge storm of 13th July 1967 (Hardman, 1968; Meaden, 1984), and the Teignmouth storm of 26th January 1984 (Bailey and Mortimore, 1984). These examples highlight that a few minutes after large hail began to fall a tornado occurred usually to the right of the hail swath(e). TORRO intends to encourage increased investigations of the damage associated with storms producing damaging hail in order to establish whether tornadoes were present too. The relationship between hailstone size and the lightning frequency of British storms will also be considered to examine whether those storms displaying lower lightning frequency are those which in general produce the largest hail (Blevins and Marwitz, 1968). The use of hailpads, about which TORRO provides advice, would be especially useful for TORRO observers to investigate the relationship between hailstone size and lightning frequency in storms. Much can be learned about the storm cell from which large or giant hail fell by examining the size and shape of the hailstones, the size and number of concentric layers of opaque ice (due to the presence of numerous tiny air bubbles) and clear ice, and the existence of any breakages within the hailstones (using thin sections viewed through transmitted and polarised light). Insights into storm characteristics such as cloud

Table 1: The TORRO hailstone scale.

| | | |
|---|---|---|
| Ordinary hailstones | less than 5<br>5-10<br>11-15<br>16-20 | grain, shot, sago<br>pea<br>mothball<br>cherry, marble |
| Large hailstones | 21-25<br>26-31<br>32-37<br>38-43<br>44-50 | large marble, large grape<br>walnut<br>horse chestnut, pigeon's egg<br>golf ball<br>small hen's egg |
| Giant hailstones | 51-62<br>63-75<br>76-87<br>88-100 | hen's egg, small peach<br>tennis ball, large peach<br>medium to large orange<br>medium to large grapefruit |
| Super hailstones | 101-125<br>Over 125 | melon (French)<br>see *J. Meteorology*, vol.2, no.19, pp.200-205 |
| Some exact diameters are: table tennis ball 38mm, golf ball 41mm, tennis ball 68mm, cricket ball 73mm, baseball 74mm | | |

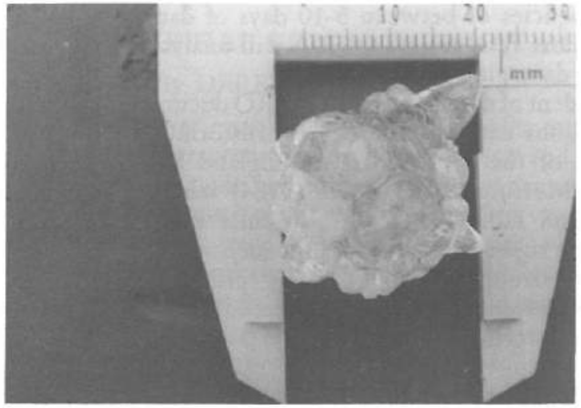

Fig.1: Large hail at Carmarthen, south Wales, on 13th November 1974, photographed by Mr. D. C. Smith of Towy Castle.

temperature, updraught speeds, fall speed of the hailstones and hailstone-growth times can be ascertained (Ludlam, 1961). The existence of foreign matter in hail is important. For example, the coke found in the large hail that fell in the Bournemouth-Poole area on 5th June 1983 suggests the existence of a tornado which lifted the coke from a surface site into the hailstorm. Similarly, observations of waterspouts near the Brighton coast later on the same day provide an explanation for the large crab which came down with marble-sized hail in Brighton (Meaden, 1983).

In an attempt to produce better uniformity in the reporting of hailstone sizes the TORRO Hailstone Scale has been devised (Table 1) (*J. Meteorology*, 9(92), 1984, 247-248). Similar standardisation will be attempted for hailstone shapes. Hailstones may be of diverse shapes including spheres, flat ovoids, "fried-egg" shapes, star-shapes, cubes, totally irregular and spiky "chunks of ice" as well as agglomerations of several shapes. Photographs, especially when showing hailstones alongside measuring rulers or standard objects, are particularly useful for TORRO records (Fig.1). If observers are able to collect large and giant hail, and preserve it in freezers, TORRO will provide the facilities for thin-section analysis.

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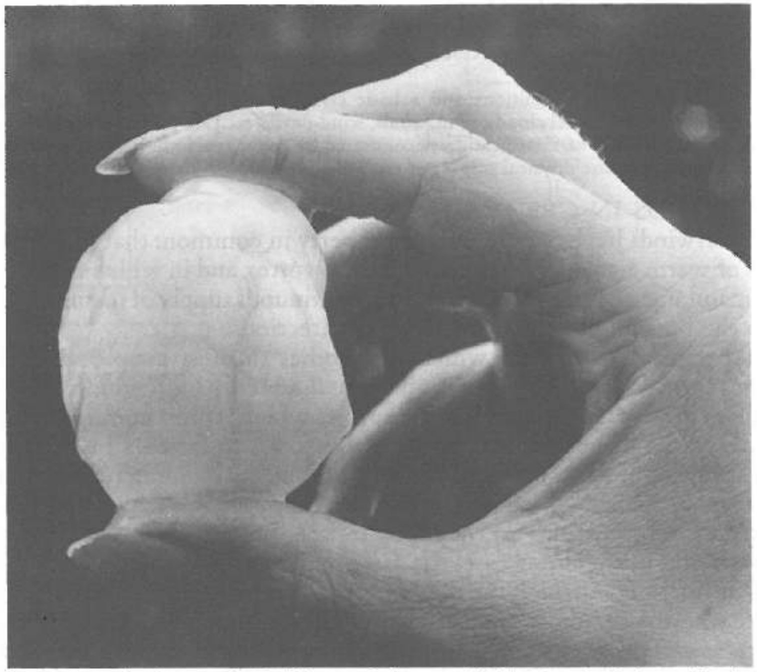

Fig.2: Giant hailstone which fell at Melksham, Wiltshire, in association with the severe local storm and tornado of 13th July 1967. At the nearby village of Holt a cat was killed by a hailstone.

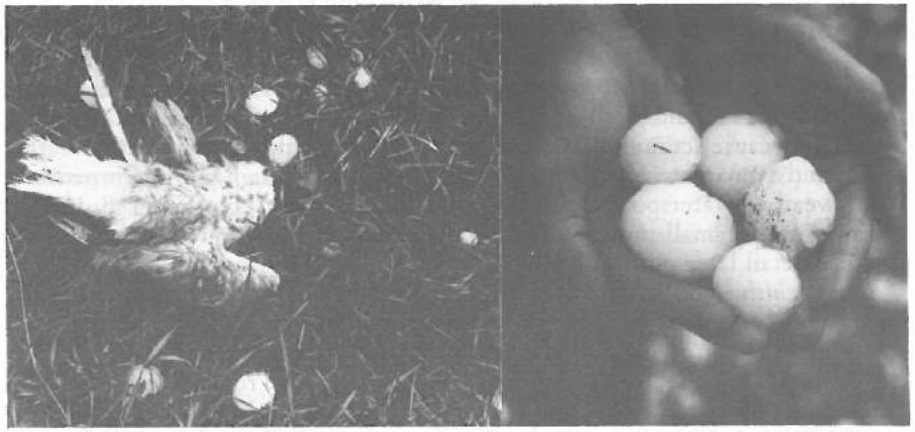

Fig.3: A black-headed gull killed by a hailstone over 50mm in diameter at La Tranche-sur-Mer, France, on 11th July 1984 (photographs by Michael Dean).

# THE CLASSIFICATION OF WHIRLWIND TYPES AND A DISCUSSION OF THEIR PHYSICAL ORIGINS

By G. T. MEADEN
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*Abstract.* In this paper definitions and a basic classification scheme for all whirlwind types (tornadoes, waterspouts, funnel clouds, whirlwinds, wind-devils, etc.) are presented in a scheme which overcomes the difficulties of classification encountered by other researchers. This is followed by a simplified discussion of the physical origins of the most important whirlwind types.

## WHIRLWINDS IN GENERAL

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.

The species of whirlwind which first comes to most people's minds is the terrifying tornado, with its reputation for undoubtedly high wind-velocities and consequent destructive power. But the species which is most commonly observed is a lesser variety, the humble wind-devil, known to farmers in Britain as the impish scatterer of new-mown hay. These are the outstanding representatives of the two main whirlwind classes, which we may call the major and the minor whirlwinds, representing as they do, in the former case, the bad-weather whirlwind and in the latter case, the fair-weather whirlwind.

This distinction, in which the mighty tornado is obviously the attendant of bad weather whereas the most typical wind-devils so often occur under sunny skies, brings us to our primary definitions, and allows us to present an entire scheme of classification for all whirlwinds – as here shown in Fig.1.

*Minor whirlwinds or wind-devils* consist of vortices of rising warm air in which the gyratory motion starts or appears to start at ground level and is often rendered visible by the levitation of dust, sand, smoke or light debris, etc. There may be an accompanying high-pitched or low-pitched sound, depending on size. It is usual for these vortices to develop from thermal plumes, induced by solar heating, which were set into rotation by some means. The weather is usually sunny, but on some occasions a land-devil or a water-devil is associated with some particular small fair-weather cumulus. In the case of a water-devil (which is a fair-weather whirlwind over a water surface) the air may be humid enough for the formation of a fair-weather waterspout, consisting of a slender spout of condensed droplets reaching up to a small cumulus. These various minor whirlwinds will be discussed in more detail later on.

*Major whirlwinds* also consist of ascending vortices of air, but these vortices can be extremely violent because they enjoin and rise to a cumulonimbus or a towering or fast-growing cumulus in which part of the immense updraught into the cloud has been set into rotation by some means. Such rotation most typically commences *inside* the cloud, and the gyratory motion, although a continuously-rising one, paradoxically extends its influence gradually downwards towards ground (or water) level.



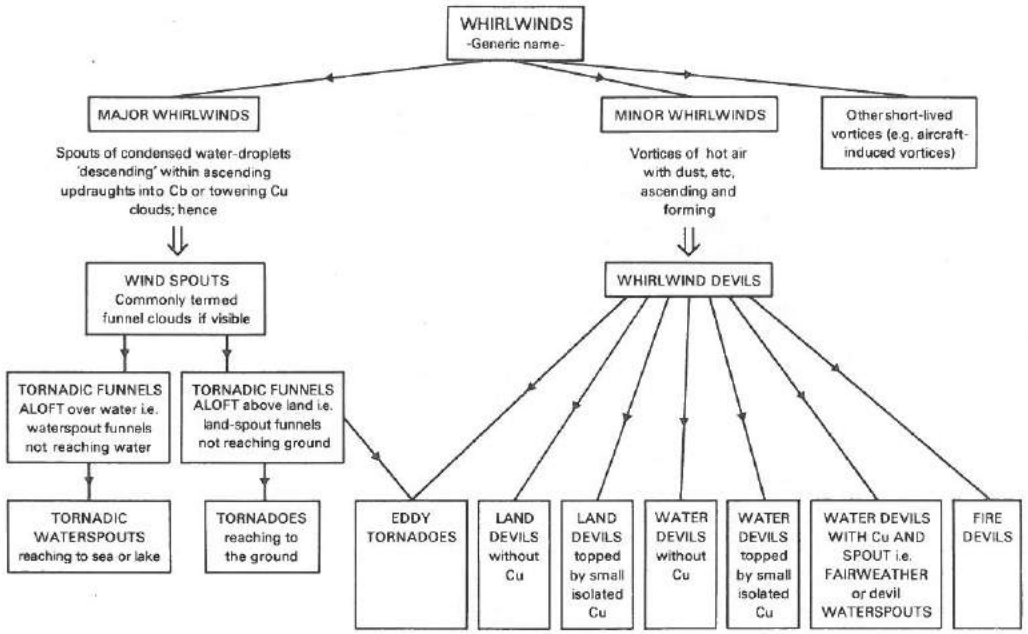


Fig.1: A classification scheme for all whirlwind types.

In many cases the air is so humid and the gyrations so intense that water vapour condenses within the vortex of reduced air pressure; this renders visible a funnel-shaped cloud of water droplets *which descends downwards within the rapidly-rotating and ascending helix.* Provided that the gyrating winds reach ground-level (whether or not an associated funnel of cloud droplets does as well), the whirlwind is termed a TORNADO – and in the case of a water surface, a waterspout, or more strictly, a TORNADIC WATERSPOUT. Specific definitions will be given later. The noise accompanying tornadoes and tornadic waterspouts is an intense roaring sound.

The distinctions and qualifications so far discussed enable unequivocal assignment of marginal whirlwind classes to be made (see Fig.1), at the same time avoiding the difficulties encountered by Forbes and Wakimoto (1983) and Idso (1974), among others.

The physical origins of the principal whirlwind subclasses displayed in Fig.1 will now be discussed briefly.

## WIND-DEVILS

A convenient starting point for gaining a qualitative understanding of the dynamics involved in the development of all whirlwinds is the humble "thermal" and its energetic "offspring" the fair-weather whirlwind. From there, it is natural to consider that special product of nature or mankind, the fire-devil, and after that tornadogenesis itself.

The *fundamental* criterion is the need for *instability.* Air, near to the earth's surface and heated by the sun, is strongly warmed by radiation from the hot ground, producing a thin super-adiabatic layer of air whose temperature close to the ground may be 15 to 20 deg. C hotter than at a level only a short distance higher. This heated layer is unstable because warm air is lighter than cold, and cannot for long underlie cooler air. At certain locations, probably the hottest, the heated air bursts upwards, like bubbles of steam rising from the base of a pan of boiling water. The air thus lost by convection is steadily replaced by more hot air flowing in from adjoining parts of the hot-layer region. In this way, a convective current of rising warm air, known as a 'thermal', is maintained; sometimes it is topped by a small cumulus cloud.

The second basic criterion is the need for *convergence.* That is, we have to consider the development of spin as the warmer air flows horizontally into the warm-air column from all sides.

At most times, warm-air columns or thermals are in a dynamically quasi-stable state. Under cloud-free skies they can persist all day, vanishing only with the setting of the sun or with the growth of too much cloud cover. In the absence of topographic or atmospheric perturbations there is no convergence – just straight in-flow. But if definite convergence commences, in either sense, then a whirlwind devil is born. This may be called, more simply, a wind-devil.

This can happen, for example, in the presence of a shear wind-field caused by topographic anomalies adding angular momentum to the inflowing wind. Good examples occur daily in favoured desert situations where such whirlwinds are common in cloudfree weather (Sinclair 1969). Any accidental or deliberate gyratory movement of a critical size not far from a thermal can induce the air to turn about that point, with the result that the then-converging air gyrates the thermal and sustains it as a new-born whirlwind.

Any kind of shear wind-field or micro-front seems capable of setting a whirlwind-devil off. Relatively common near coasts are wind devils formed on a sea-breeze front, where the wind-change boundary-zone is liable to set thermals rotating. The downdraught boundaries of an advancing thunderstorm sometimes interact with insolational thermals producing wind-devils close to cumulonimbus clouds (Idso 1974).

## FIRE WHIRLWINDS, OR FIRE-DEVILS

If the conditions for convergence are present, a whirlwind state can be induced by burning a fire, thus creating a strong updraught. This gives rise to the fearsome fire-devil in which the force of the wind intensifies the fire greatly above its normal state. This is because the angular velocity of the converging air increases in proportion to the decreasing radius due to conservation of angular momentum. Fire disasters in big forests or cities draw in huge volumes of air, and can create lethal fire-devils in the presence of convergence. Even small fires can be deadly; for example, in September 1978 stubble burning produced a fire-devil which destroyed a £100,000 farm in Hampshire. Mike Rowe once saw a fire-devil dancing by a bonfire on the evening of 4th November 1972. This reminds us that fire-devils can occur at night-time, when normal wind-devils cannot, because fire-devils have self-sustaining thermal plumes which overcome a lack of atmospheric temperature instability. Excellent experimental work in this field has been done at the University of Clermont in France directed by Professor Dessens (e.g. Dessens 1962; Church, Snow and Dessens 1980).



## WHIRLWIND SPIRALS IN CEREAL-FIELDS

Here we briefly mention that one species of wind-devil has a predeliction for forming at dusk! This is the whirlwind which produces those beautiful, near perfect circles in cereal-fields by flattening the crops with a spiral pattern (Fig.2). Our research has indicated that they commonly form when thermal plumes are weakening for want of inflowing buoyant air (such as towards sunset) but are momentarily set rotating by a net angular momentum present in the wind-field (Meaden 1984, 1985). This may be similar to the sudden rush and intensifying spin (often with accompanying noise) which happens to outflowing bath-water in the terminal emptying stage of a bath.

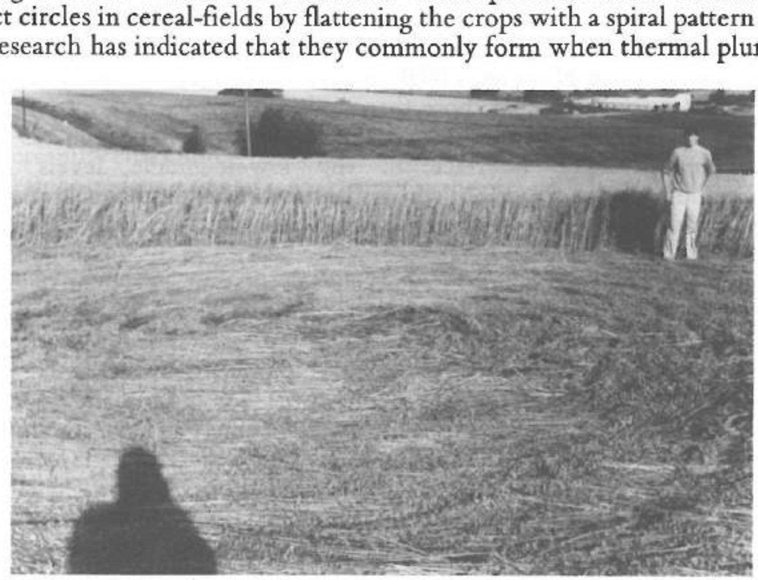

Fig.2: An area in a cereal-field flattened by a standing whirlwind (wind-devil), photographed in Wiltshire by Ian Mrzyglod. The spiral wind-flow can be seen.

## TORNADO DEVELOPMENT IN ISOLATED STORM CELLS

Here we consider isolated storm cells where the atmospheric instability and other factors are such that non-thundery cumulonimbus clouds develop into severe thunderstorms or, in some cases, severe local storms with tornadoes and/or large to giant hail.

Such storm cells have qualities relevant to this inquiry. The cells are meso-scale, low-pressure systems with strong inflowing winds and powerful updraughts and downdraughts. These systems have cyclonic circulation (anticlockwise in the northern hemisphere) which is the consequence, ultimately, of the earth's rotation; if a tornado develops, it too turns in the same cyclonic sense.

So, where does the rotation commence which, eventually, leads to tornado development?

What conditions start it off and permit it to develop?

Why do only a small fraction of severe storms produce tornadoes? Why indeed are tornadoes comparatively uncommon events?

The answers to these questions, in so far as thunderstorm cells are concerned, have been clarified in recent years by a development in radar-instrumentation known as Döppler weather radar. Using two instruments a known distance apart one can determine the wind direction and speeds at different heights within a storm cloud. These methods have enabled researchers at the National Severe Storms Laboratory in Norman, Oklahoma, and elsewhere to study air motion inside severe storms including those that produce tornadoes.

It was discovered that when a tornado develops it originates at the downdraught-updraught interface in the lowest-middle levels of the cumulonimbus. Warm moist air enters the forward right flank of the storm causing a persistent updraught which is forced to turn as it ascends due to (a) the variation of wind-speed with height (i.e. wind shear), and (b) the proximity of a downdraught of drier colder air. The initial weak rotation is cyclonic over a large diameter. Gradually, the spiralling extends upwards and downwards, the speed of rotation increasing as the diameter diminishes. This nascent tornado remains out of view within the cloud for a long time. For example, in the tornado of 24th May 1973 at Union City, Oklahoma a 4km long tornado column was detected for a period exceeding 20 minutes before a funnel cloud emerged from the cloud base. When the tornado was fully mature, it was 10km in height and reached from ground level to the top of the parent cloud.

In general, a spinning vortex beneath the cloud-base displays a visible funnel of condensed cloud droplets only if the spin-rate and moisture-content are great enough. In fact, some vortices bring their devastating winds down to ground-level without the obvious visible warning provided by a definite funnel cloud. But usually there is a well-formed funnel, and at ground level its diameter may range up to 10 to 100 metres, or even 1,000 metres in exceptional American events.

Some British examples of tornadoes formed from severe local storms of this type include the Horsham tornado of 5th September 1958 (Ludlam and Macklin 1960, Rowsell 1960) and the Trowbridge-Melksham tornado of 13th July 1967 (Harding 1968, Meaden 1984).

Supercell storms like these can produce tornadoes in other ways: (1) from the shear forces on the periphery of strong downdraughts, and (2) the shear zone along the storm's gust front, i.e. at the leading edge of the main outflow.

## TORNADOES IN COLD-FRONT SITUATIONS

Tornadoes in thundery cold fronts (together with thunderfree line squalls) are responsible for a high percentage of Britain's and Western Europe's tornadoes. Large multiple outbreaks are common in England and Wales from mid-September to mid-February. The largest in the records of TORRO in the last 20 years are:

| | | |
|---|---|---|
| *thundery cold fronts* | 1966 November 15 | 19 known tornadoes |
| (or *thundery* | 1966 December 1 | 26 |
| *instability trough,* | *1974 January 10-11 | 21 |
| marked *) | 1981 October 20 | 31 |



| | | |
|---|---|---|
| | 1982 September 21 | 23 |
| | 1984 February 8 | 21 |
| *thunderless cold fronts* | 1971 December 19 | 17 |
| *with line squalls* | 1981 November 23 | 105 |

The multiple outbreaks of 1974 January 7th, *1975 January 12th, and 1978 January 3rd probably had numbers comparable to those in the thundery cold-front list, but TORRO tornado-collection methods were not as efficient prior to 1980 as they are now.

### *(a) Thundery Cold Fronts*

The essential condition is that a cold front has an extensive shear zone all along the cold air boundary where it is over-running the pre-existing humid warm air. At intervals along the front thundery cells develop, some of them supercells. The most common of the widespread outbreaks of tornadoes in Europe occur in southern Britain on cold fronts in association with deep depressions moving east near Scotland when the general winds are strong to gale-force. It seems that many of the thundery supercells on these cold fronts are tornado-bearing because the physical arguments of the preceding section apply. In some cases tornadoes may have developed in the manner of line-squall tornadoes discussed in the next section, whereas in some others tornado formation may have been associated with gap edges in line-convection elements of ana-cold fronts (Elsom 1983). The latter mode of tornado formation would likely to be related to the interaction of gust fronts from adjacent cumulonimbus cells.

### *(b) Line Squalls (Thunder-free) Cold Fronts*

Europe's biggest tornado outbreaks may possibly occur in severe line-squall situations. Europe's biggest known outbreak (and the second biggest known in the world) was monitored and researched by TORRO a few years ago. 105 damaging tornadoes were found to have descended on north Wales, central and eastern England during the space of six hours while a thunderless line-squall traversed the area (Rowe and Meaden 1985). Alfred Wegener recognised the effectiveness with which a line squall could produce a tornado in 1917 and he gave the first generalised explanation (Wegener 1917, 1928).

Line squalls are associated with cold fronts which, in north-west Europe, most often surge from the Atlantic, pushed along by polar maritime air overrunning pre-existing warm air. They commonly cross Britain from N.W. to S.E. or from W. to E. Pronounced line squalls may precede the main cold front by up to a few kilometres. In an ideal case the nose of overrunning cold air is a long horizontal vortex, perhaps several hundred kilometres long (Fig.3 a and b). Moist warm air is rising into it all along its length.

Irregularities of terrain, or irregularities in the atmosphere, cause a section of the vortex to become inclined, with one end dipping slightly and the other end rising (Fig.3c). The lower end, in being pushed down towards the rising light moist air, sucks buoyant air in and upwards in the efficient manner that all vortices do. This improves the updraught, quickens the spin and lowers the pressure, so lengthening the inclined vortex and inclining it still further. Hence the lower end (which is the more southern end in the case of eastward-moving line squalls) turns

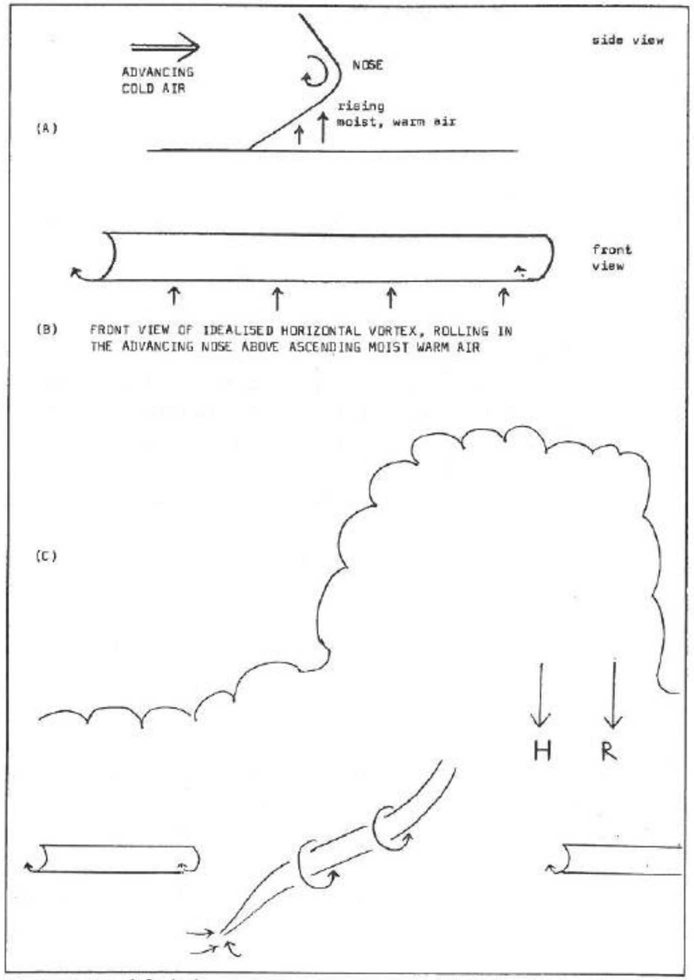


Fig.3: A simplified, diagrammatic representation of tornado formation in a line-squall situation.

increasingly towards the ground, while the other end rises. Eventually, the lower end reaches the ground, when the sense of rotation can be seen to be cyclonic (anti-clockwise in the northern hemisphere). Presumably, the system is now operating at maximum efficiency with regard to the rate of intake of warm buoyant air; this would explain why the tornado vortex, like so many other natural vortices, strives to terminate on a suitable boundary. This may also be the reason why line-squall funnel clouds grow so rapidly into mature tornadoes. It may also explain why TORRO has no record of overland funnel clouds without tornado-descent in the autumn-to-winter period (say mid-October to mid-March). At the same time it suggests that tornadoes of this type have a tendency to descend with a characteristic 'sideways' component, pointing somewhat to the right.



Notice that in the system as described, the tremendous tornado updraught of moist air must build up huge convective clouds slightly to the left of the tornado's ground track. This accords well with the general observation that (1) the heavy rain, the large hail and the deeper clouds all occur significantly to the left of the tornado track, and (2) large objects levitated by the cyclonically-rotating tornado are carried forwards and to the left.

Contrariwise, if cells on the coldfront squall line are giving heavy rain associated with an intensifying updraught, the main squall-line boundary will be disturbed, and may throw off to the right side of a cell an occasional inclined vortex in the form of a descending tornado.

## TORNADO DEFINITIONS

We are now in a position to provide definitions for the common "tornado" and "tornadic funnel cloud" which take account of the discussion in this paper.

*TORNADO:* a vortex of strong winds, generally making a loud roaring noise, which reaches to the ground after descending from cloud-level, and which is associated with the updraught into a cumulonimbus, towering cumulus or line squall, and which is usually accompanied by a visible condensation funnel which itself may or may not reach the ground.

*FUNNEL CLOUD:* If no wind vortex reaches the ground but a funnel of condensed cloud droplets is seen aloft, then only a *funnel cloud* is reported.

## WATERSPOUT DEFINITIONS

All the tornado-forming systems described in this paper will produce waterspouts if they pass over a water surface instead of a solid surface. These may be termed tornadic waterspouts in order to distinguish them from much weaker waterspouts which are instead akin to fair-weather land-devils. The latter are, in reality, insolational whirlwind devils over water, but, in contrast to the spoutless land-based variety, they have a narrow spout because of the greater humidity and the better concentration of energy into the vortex. Such spouts usually, if not always, vanish upon their approach to land. A two-part definition is therefore appropriate.

*WATERSPOUT, TYPE 1:* a vortex of strong winds which reaches to a water surface after descending from cloud-level, and is associated with the updraught into a strong convective cloud or line squall, and is accompanied along part or all of its length by a visible condensation funnel. These spouts often make a roaring noise, and can be termed *tornadic waterspouts.*

*WATERSPOUT, TYPE 2:* A slender spout of condensed water droplets extending part or all of the way between a small fair-weather cumulus cloud and a water surface which is agitated into spray by the inflowing winds. They may be termed *fair-weather waterspouts* or *devil waterspouts* because their origin is insolational. It is probable that, like land-devils, the whirling winds commence in the super-adiabatic air near the water surface and then gradually extend their influence upwards.

Finally, we close with some remarks about the effect that a strong waterspout has on a water-surface. Because water is a fluid and the surface is obstacle-free, a better development of the inflowing wind-pattern is possible with a waterspout than with a tornado. Hence the sea-surface is able to display beautifully the spiral wind-inflow pattern (as in the standing whirlwind pattern in the flattened crops of Fig.2). In addition, the energy is more readily concentrated within the waterspout vortex, thus permitting narrower spout formation than for tornadoes. The weaker waterspouts consequently disperse upon making land-fall because of the effect of friction upon the inflow of air (besides there being, over land, less moisture to form a visible condensation funnel). Often, a cylindrical sheath is clearly visible outside the inner vortex. This spray-filled region denotes and displays well the region of maximum ascending winds.

## CONCLUDING REMARKS

The essential features of the various types of whirlwinds have been discussed in this paper with the aim of arriving at clear fundamental definitions. This has been aided by presenting a general classification scheme which shows whirlwinds as falling into two basic groups, the major and minor whirlwinds. Waterspouts appear in both groups because they consist of two distinct types. Type 1, the tornadic waterspout, belongs properly to the major whirlwind class which includes true tornadoes, while type 2 is a minor whirlwind, being a fair-weather wind-devil over water with a narrow weak spout.


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# TORNADOES IN BRITAIN: WHERE, WHEN AND HOW OFTEN


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*Abstract:* The advances made by TORRO in coordinating the collection of eyewitness reports of tornadoes and in documenting tornado events from newspaper reports and site investigations are outlined. Nearly 1,000 British tornadoes are now documented in TORRO files for the period from the 1950's to present day. Using this information, the annual, monthly and diurnal distribution of British tornadoes are discussed. Further, the first compilation of county tornado frequencies is presented as a provisional indication of the tornado risk faced by different regions of the country.


## INTRODUCTION

In its first decade TORRO has made remarkable advances in our understanding of whirlwinds, especially tornadoes, in Britain. This paper outlines the present state of our knowledge concerning the frequency, timing and geographical distribution of British tornadoes.

## HOW FREQUENT ARE TORNADOES? ARE TORNADOES ON THE INCREASE?

Before TORRO was established there had been only three attempts to discover the frequency of tornadoes in Britain. Brooks (1954) mapped 23 tornadoes in England covering a 300-year period, Lamb (1957) listed 54 tornadoes for England for the period 1868-1950 (based on *Meteorological Magazine* reports), and Lacy (1968) discovered 78 tornadoes for the period 1963-66. In contrast, TORRO has shown that over 100 tornadoes can occur a single day in England and Wales alone and that each year there may be as many as 31 days on which tornadoes form in Britain (Fig.1).

Improved documentation of tornado events also arises because of the advances made by TORRO in recognising a tornado event from newspaper damage reports. Too often newspaper reporters are unsure whether to attribute damage to a tornado or not. Instead, they resort to the use of general terms such as freak wind, a whirlwind, a mini-typhoon or even a hurricane. Even when the evidence for a tornado is overwhelming there is a reluctance to accept a tornado as the cause unless it is labelled as a "freak" tornado. This indicates a general lack of awareness by the press and the public that tornadoes in Britain are not all that uncommon. However, an indication that the press are beginning to realise that tornadoes are not "freak events" came on 3rd August 1984 when, for example, the *Guardian* and BBC early evening television reported the Gotham tornado and, for the first time ever, explained that "each year Britain experiences 50 tornadoes but not usually as severe as this". It appears that TORRO's findings are at last becoming widely known.

The press and public uncertainty as to the cause of a wind-damaging event arises because very few tornadoes are actually observed in action, let alone photographed. This is because darkness may prevent them being witnessed, direct line-of-sight of a tornado may be obscured by precipitation, low cloud, hills, buildings and trees, or there may be no potential eyewitness present such as in many rural areas. Further, a clearly defined vortex may frequently be enveloped and somewhat obscured by whirling dust and debris (Elsom and Meaden, 1984). However, on some occasions it is the presence of swirling debris or leaves which reveals the presence of a tornado in the area rather than seeing the condensation funnel cloud. For example, the tornado vortex may not be visible near the ground because the rotation strength and pressure reduction within the vortex are insufficient to cause condensation of water droplets which form the visible funnel cloud. On some occasions, Idso (1974) suggests that no condensation funnel is present because the humidity level is too low.

In the absence of a vortex sighting, it is necessary to confirm the existence of a tornado through details provided by newspaper reports and investigations of the damage sustained at a site. Obviously, newspapers are written for dramatic effect and are not written in order to provide an accurate checklist of damage effects which can be related to tornado activity. Nevertheless, press reports can provide descriptions of damage effects that TORRO recognises as clearly pointing to a tornado being the cause of the damage. In other instances the press report brings TORRO's attention to a possible tornado event which can then be investigated. As the number of tornadoes being reported is increasing, TORRO needs to establish regional (county) investigators of possible tornado damage sites. It is preferable that a site is visited but if this is not possible individuals mentioned in the report can be contacted for a telephone interview or to be sent a postal questionnaire by TORRO. The success of TORRO's investigations of current and past tornado events is demonstrated by Fig.1. The year-to-year fluctuation in tornado statistics may be explained by varying frequencies of synoptic and meteorological conditions suitable for tornado formation (e.g. large tornado outbreaks in 1966, 1974, 1981 and 1982) but the long-term trend of an increase in the number of

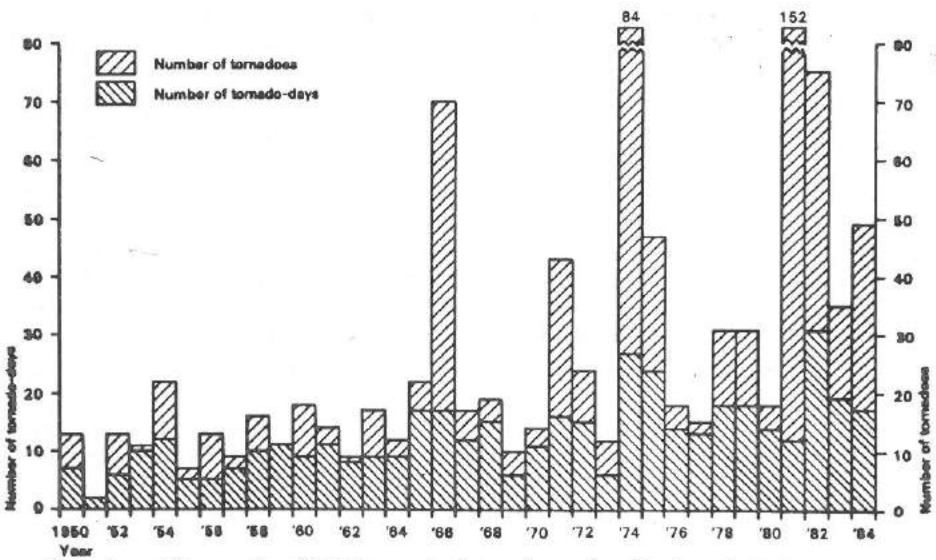


Fig.1: Annual frequencies of British tornado-days and tornadoes for the period 1950-1984.



tornado-days and tornadoes is explained by the improvements in tornado documentation promoted by TORRO. The mean annual number of tornado-days documented has increased from seven days in the 1950's to 12 days in the 1960's, to 16 days in the 1970's, to 19 days in the 1980's. Even more dramatic has been the rise in the number of tornadoes documented with the mean annual number of tornadoes increasing from only 11 for the 1950's, to 21 for the 1960's, to 32 for the 1970's to 66 for the 1980's. However, it should be borne in mind that these figures still underestimate the true number of tornadoes which occur in Britain each year given that a vast number of tornadoes, each perhaps affecting an area of only 0.1-0.2km$^2$, pass unobserved and unreported in rural areas.

The evidence which is sought in order that a tornado may be designated as the cause of damage includes:

*a) a narrow damage path.*

Damage by tornadoes is characteristically confined to a narrow path, varying from a few metres to a few hundred metres in width. The width of the track may appear to vary because of fluctuations in the intensity of the tornado, varying susceptibility of property to damage, availability of potentially damageable property, and topography, as well as because of secondary damage caused by objects lifted and thrown outwards from the tornado causing damage further afield. Frequently, tornado damage lies along a straight track which occasionally deviates slightly from a straight line (usually towards the right) towards the end of the track as the tornado begins to dissipate (e.g. the Oxford tornado of 16th October 1966, the Eynsham tornado of 13th January 1983, and the Bicester tornado of 21st September 1983) but sinuous tracks (e.g. the Smethwick tornado of 13th August 1982) and tracks which show abrupt changes in direction may occur (e.g. the Teignmouth tornado of 26th January 1984). Very intense tornadoes in the United States have revealed swath(e)s of varying degrees of damage within the tornado track itself due to suction vortices (or spots) which rotate slowly around the fringe of a tornado core (Fujita, 1970). However, site investigations have yet to document this form of damage in British tornadoes although TORRO has some uninvestigated reports on file of trenches scoured into soft earth or sand. Surprisingly, one of the best cases in TORRO's records which may suggest the existence of suction vortex damage swath(e)s is one of the earliest known British tornadoes, namely the Scarborough tornado of August 1165 when eyewitnesses reported horse-shoe shaped imprints along the tornado track. Increased site investigations of the more devastating of British tornadoes should reveal suction swath(e)s in the future. Close examination of damage patterns produced by tornadoes is particularly useful in documenting the direction of rotation of tornadoes. For example, tracing the trajectory of debris may reveal whether a tornado was characterised by cyclonic rotation which is the more common direction. In 1978 Fujita introduced the concept of thunderstorm downbursts and smaller microbursts which may cause damage. However, damage due to tornadoes and microbursts can be distinguished because microbursts seldom produce a damage track that is less than a kilometre in width and the damage patterns within the track reveal a diverging airflow rather than the converging airflow of a tornado. It is not unusual for damage tracks due to tornadoes, say formed in association with a cold front, to be embedded in a broader area of lighter or intermittent structural damage caused by thunderstorm downbursts, strong winds, and line squalls.

*b) explosive or suction effects.*

Tornadoes are characterised by a steep pressure gradient between the outside and the inside of the vortex and this may cause windows (and even the frames), doors, walls, and roofs to burst outwards and for objects to be sucked through open windows, up chimneys, and through other openings in structures. The pressure gradient has yet to be measured in British tornadoes but the Smarden tornado of 5th September 1980, described as a "black tube", passed only about 40-45 metres from a barograph which displayed a rapid fall of 7mb and an immediate recovery of 5mb. People frequently notice the abrupt pressure changes associated with tornadoes through the effects on their ears or by the effects of induced air movements within their homes such as for example during the West Midlands tornado of 7th December 1982 (Fullen and Smith, 1983). The most damaging "explosive" effects are associated with poorly vented structures such that the localised steep pressure gradient produced by a tornado passing near to a structure may burst roofs and walls outward as their connections weaken. However, the significance of lesser "explosive" damage may escape an untrained observer and it is possible that differentiation between a window bursting outwards rather than blowing inwards would not be made in a newspaper report or during casual observation. Not all "explosive" effects need be attributed to the steep pressure gradients existing between the outside and the inside of the tornado (Mehta et al, 1976). Some explosion effects may simply be due to wind-induced forces whereby small openings in houses and buildings can effectively "vent" the structure. For example, a well constructed house with all windows and doors tightly closed except say, one window on the upwind side (perhaps broken by a piece of debris), may explode in tornadic winds because of the ram-pressure effect, while a similar house with the lee windows or vents open may suffer only light damage (Davies-Jones and Kessler, 1974).

*c) shear effects.*

A distinctive characteristic of tornadoes is the concentrated and intense wind shear which may result in the twisting and/or corkscrewing of tree tops, branches or trunks. Trees may reveal unmistakeable signs of this twisting action on the wood where the branch or trunk has been snapped. Such damage is seldom described in detail in newspaper reports so this needs investigation in the field. This effect can be striking as for example, in the Biddenden-High Halden tornado incident on 20th October 1981 when "huge oak branches, half a metre in diameter, were twisted round like wringing out a wet cloth". When confirming the existence of shear effects on trees, care must be taken that this twisting effect was not produced by a tree branch or trunk partially breaking and commencing to fall in one direction, and then, being constrained by something other than wind, changing its direction of fall (Evesson, 1969).

*d) heavy objects lifted and/or objects carried long distances.*

When dense heavy debris such as tiles, bricks, planks, etc. are carried upwards, very strong updraughts are indicated and Evesson (1969) concluded that



updraughts capable of lifting such objects to any significant height above the ground (say, 15 metres) are almost exclusively associated with tornadoes. Flying objects have the potential to cause serious injury because of the force with which objects are carried along. Examples include roof tiles embedded in neighbouring roofs and walls, debris embedded deeply in the ground (e.g. the West Midlands tornado of 7th December 1982), pieces of roofing embedded in trees (e.g. the Coldean tornado of 20th October 1981), and fragments of glass embedded several centimetres in woodwork (e.g. the Llandissilio tornado of 12th December 1978). In extreme cases, exceptionally heavy objects such as vehicles may be lifted a few centimetres or even metres while mature trees may be completely uprooted. The north-west London tornado of 8th December 1954 was observed to cause a motor car at Acton to float some five metres in the air. Caravans appear particularly susceptible to lifting by tornadoes and reports of caravans being lifted and turned upside down or smashed into pieces (e.g. the Goostrey tornado of 21st March 1983) frequently figure in tornado damage reports.

In some tornado incidents light debris and objects may be lifted and carried considerable distances and some of the most remarkable effects of tornadoes may be attributed to those objects being later released to produce showers of frogs, fish, hay, shells, seaweed, sand, etc.

*e) unusual sustained roaring noise distinct from the ordinary sound of the wind.*

The approach of a tornado is often likened to the sound of an approaching express train or low-flying aircraft. The strong wind shear of the vortex produces a distinctive roaring sound distinct from the usual sound of the wind. However, describing sound is rather subjective and a variety of terms are employed by witnesses. The East Sussex tornado of 21st December 1983 was described by one witness as a "humming noise which changed to a violent scream" while others said "it was like a bomb going off". The Doncaster tornado of 14th January 1984 was described as making an "incredible noise like thunder", the Ivybridge tornado of 31st July 1983 described as making a "whirring sound like a wind tunnel", and the Petersfield tornado of 13th October 1982 as making a "whistling noise and then a great roar". In general, witnesses report that many of the weaker tornadoes, and funnel clouds aloft, produce more of a whistling or rushing sound.

## WHEN DO TORNADOES OCCUR?

Tornadoes develop from a parent storm which is usually a cumulonimbus but may be a towering cumulus (cumulus congestus) as described by Terence Meaden in an earlier paper in these conference proceedings. The formation of an appropriate parent storm is dependent upon the synoptic situation and its associated meteorological conditions and the way in which the meteorological conditions may be modified by the diurnal variation in solar heating as well as by surface features. This leads to pronounced seasonal and diurnal cycles in tornado frequency.

Elsom and Meaden (1984) showed that the frequency of days which give rise to tornadoes each month are higher from June through January, with a peak in September, and lower from February through May. The minimum in tornado activity during the late winter and spring is related to the lesser frontal activity of this period and to the seas around Britain being normally at their coldest at this time. Without a particularly unstable airmass or marked front there is insufficient surface heat to provoke the vigorous convection necessary for the development of thunderstorms suitable for tornado formation. However, this does not preclude an exceptionally well-defined cold front from producing a large outbreak of tornadoes as happened in February 1984 (Elsom, 1984). A more striking seasonal variation is revealed when the number of actual tornadoes per month are examined. Nearly half the tornado-days in November, December and January give rise to tornado outbreaks. Elsom and Meaden (1984) classified outbreaks of tornadoes as days when two or more tornadoes occurred, that is, small outbreaks (2-9 tornadoes), medium outbreaks (10-19 tornadoes) and large outbreaks (20 or more tornadoes). Seven out of the nine medium and large outbreaks of tornadoes known to have occurred in the period from 1951-83 took place during the months of November through January in association with the passage of vigorous cold fronts or troughs. In contrast to these months, the summer months experience far fewer tornado outbreaks with, for example, only one in five tornado-days during June through August giving rise to more than a single tornado.

The British monthly distribution of tornado-days and tornadoes contrasts with the American distribution which displays a strong peak in May and June and a minimum in December and January (Schaefer et al, 1980). When the U.S. monthly tornado distribution is examined by intensity it is found that, whereas weak tornadoes peak in May and June, violent tornadoes are most prevalent in April when the temperature difference across frontal systems is strongest, and faster wind speeds aloft provide more energy. An examination of the most violent tornadoes known for Britain suggests that September, December and January are the months most prone to these exceptional events.

Although tornadoes may occur at any time of the day, the most likely time for tornado formation is during daylight hours. However, Fig.2 reveals a seasonal variation in the diurnal distribution of tornadoes. Most tornadoes in summer form

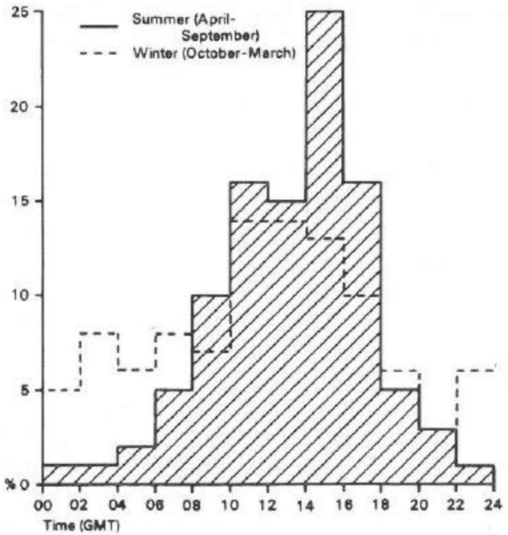


Fig.2: Seasonal diurnal distributions of British tornadoes for the period 1951-1983.



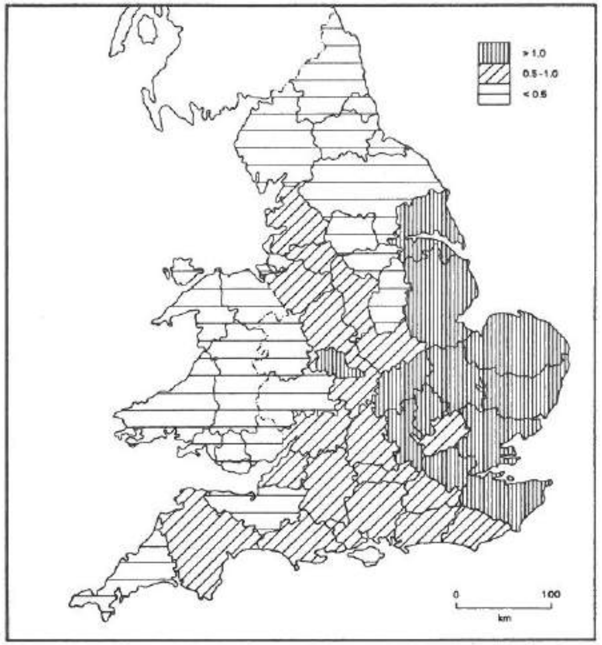


Fig.3: Mean annual number of tornadoes per county in England and Wales for the period 1960-1982.

during late morning through afternoon as is the case for thunderstorms at inland locations (Davis, 1969; Prichard, 1973). Very few tornadoes occur at night during the summer in contrast to the situation during the winter. For example, an examination of 1951-83 tornadoes showed that only 5% of summer tornadoes occurred between 2200-0600 GMT as compared with 25% of winter tornadoes. The relatively higher frequency of nighttime tornadoes during winter arises because, in the absence of solar forcing, tornado formation at night needs the dynamical forcing associated with the passage of well-defined fronts or troughs of deep depressions. The development of thunderstorms and tornadoes by such fronts during winter also benefits from the relatively high temperature of the seas around Britain at this time which aids convective activity at night (Shone, 1977).

## WHERE DO TORNADOES FORM?

Fig.3 provides details of the tornado frequency for each county in England and Wales for the period 1960-82. County totals included tornadoes lying up to 2-3km inside adjacent counties in recognition that many of the tornado tracks were not fully documented and so may have extended across the county boundary. Obviously, tornado frequencies for each county are influenced by county area and by the efficiency with which tornadoes are reported. The latter factor is a function of population density, number of large towns and cities, number of local newspapers, etc. Further, for the tornado frequencies involved, the sample period of 23 years may be regarded as relatively short and this may be the cause of some anomalies such as Hertfordshire which has a lower tornado frequency than the counties which surround it.

The topography of the counties also affects documented tornado frequencies. Although high and rugged terrain is linked with less population to report tornadoes, topography may directly influence tornado formation by modifying the meteorological conditions in the vicinity of the parent storm from which a tornado may form. For example, Bates (1963) and Safford (1970) state that hail-producing thunderstorms do not rotate but that many tornado-producing thunderstorms do rotate (Fujita et al, 1976, estimate that 50% of U.S. tornado-forming thunderstorms rotate). They suggest that tornado occurrence decreases and hail increases over significant terrain features by reducing updraught rotation in the parent thunderstorms. Such influences need further examination as does the apparent influence of the urban heat island and surface roughness of cities on weak tornadoes suggested by Elsom and Meaden (1982).

Although there are many factors which affect the county tornado frequency as shown in Fig.3, the map suggests that parts of central England and eastern England experience higher tornado frequencies than the rest of England and Wales. County tornado frequencies for Scotland and Northern Ireland were not provided because the number of known tornadoes is relatively small compared to England and Wales. Tornado reporting efficiency as indexed by population density only partly explains the lower tornado frequencies for Scotland and Northern Ireland compared with England and Wales. For example, the Central Lowlands of Scotland are densely populated, like the English West Midlands, yet very few tornadoes are reported. That the north of Britain experiences fewer tornadoes is confirmed when one examines the county frequencies in northern England. Whereas Humberside experiences (statistically) more than one tornado per year (based on the 1960-82 period) there are no known tornado occurrences in the similarly urbanised industrial counties of Tyne and Wear and Cleveland for the 1960-82 period. This highlights that the northern parts of Britain do indeed experience fewer tornadoes than the rest of Britain. This arises because the synoptic situations and meteorological conditions which produce tornadoes, such as the meeting of cold polar airmasses and warm moist airmasses of southerly origin along well-defined cold fronts, occur far more frequently over England and Wales than the rest of the British Isles. In this connection, the tornado frequency distribution shown in Fig.3 is somewhat similar to thunderstorm frequency distribution.

As the number of tornadoes on TORRO's files increases so the geographical distribution of tornadoes on a seasonal basis will be analysed and compared with thunderstorm and severe hailstorm distributions derived from TORRO's Thunderstorm and Hailstorm Divisions. Analyses will also be performed to standardise county tornado frequencies by area and to reduce the reporting efficiency bias inherent in tornado documentation so as to obtain better estimates of the tornado risk to which each county is subjected.

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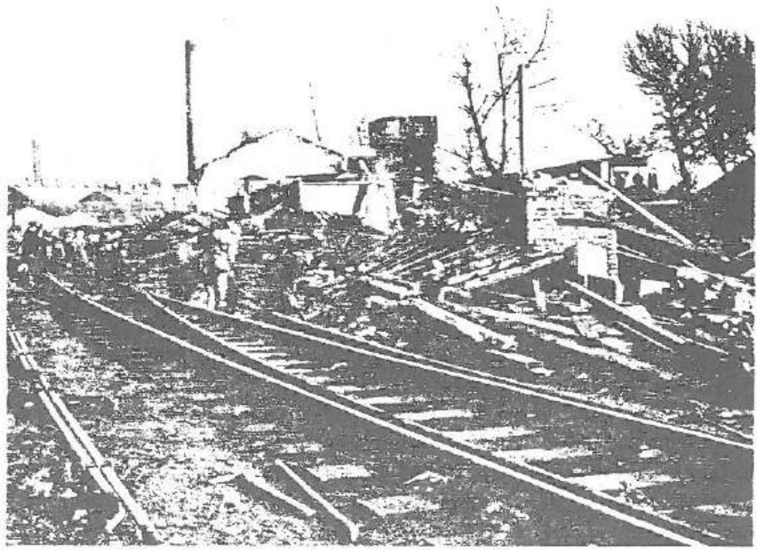

The T7 tornado, which traversed west London on 8th December 1954 and injured some 20 people, totally destroyed this factory at Acton *(Acton Gazette).* This illustrates how powerful British tornadoes on thundery cold fronts can be in the wintertime (see also photograph on p.226).

# BRITAIN'S GREATEST TORNADOES AND TORNADO OUTBREAKS

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*Abstract:* This paper describes, firstly, Britain's most severe tornadoes – those known to have reached force T6-T8 on the TORRO scale – and, secondly, the largest multiple outbreaks, that is occasions when numerous tornadoes occurred in Britain on the same day. It also serves to illustrate the types of source material which are available at different periods from medieval times to the present day.

## THE MOST SEVERE TORNADOES: FORCE T6 OR MORE

Only a small proportion of British tornadoes are known for certain to have reached force T6 or more: under 1%. Twelve of the most definite cases are briefly described in this paper. There are a few additional, chiefly Medieval, cases which could be force T6 as well. There are also several other instances in which the maximum force is unknown or underestimated, either because there were no eye-witnesses at the crucial point, or because not enough eye-witness evidence has yet become available. Force T6-T8 implies devastating wind speeds in the range 73-107m/s, or 161-240mph.

### TN1091October23. *London (TQ 3782)*

This tornado is the earliest documented tornado from the British Isles. It is known from two almost contemporary chroniclers, William of Malmesbury and Florence of Worcester. It was claimed to have demolished 600 houses and a number of churches. Obviously there is the possibility that the accounts are exaggerated, although it should be borne in mind that most of the houses then were wooden. Both writers give a very circumstantial description of how the church of St. Mary le Bow had its roof lifted off and carried a great distance with several rafters being embedded many feet in the earth.

### TN1667October23. *Welbourn to Boothby Graffoe, Lincolnshire (SK 9654-9859)*

TORRO has two independent reports of a very violent tornado near Lincoln on this date. The tornado followed a 7km-long track from S.S.W. to N.N.E. At Welbourn it demolished 44 houses and killed a boy. At Boothby Graffoe it partly destroyed the church, both timber and stonework, and threw down many houses. Houses were also demolished in the intervening villages of Wellingore and Navenby. This tornado followed the steep scarp of Lincoln Edge, and it is tempting to suggest that it may have been initiated by it. The tornado, which had a track of 60 metres or more wide, was accompanied by hail as large as pigeons' eggs.

### TN1810October14. *Southsea, Hampshire (SZ 6498)*

This event, reported in *Gentleman's Magazine* (vo.80, II, 583, 1810), may have been as severe as T8: "The town of Portsmouth was visited by a tornado, which passed in the direction of W.S.W. to S.E. and did very considerable damage. At Southsea Common four houses were levelled to the ground, and as many more so much injured as to render it necessary to take them down; besides 30 others unroofed." Haslar Hospital, the Marine Barracks, and the Government House and Chapel were among other buildings damaged.



### TN1876September28. *Cowes, Isle of Wight (SZ 4995)*

Tornado documentation improves markedly from about 1860. For the Cowes event we have newspaper reports from *The Times* and the local press, and a long description in the *Meteorological Magazine.* The tornado first appeared off Brook, in the S.W. of the Isle of Wight, as a waterspout which dissipated on reaching land. The tornado formed again south of Cowes, and wreaked havoc in the town. The Globe Hotel was wrecked, the front being blown out, exposing the bedrooms. A girl was lifted to a height of five metres and carried 50 metres. A heavy railway carriage was blown over. The tornado crossed the Solent, dropping debris on a yacht more than a kilometre offshore, and struck the Hampshire coast near Titchfield Haven. It probably then dissipated, but it formed again at Meonstoke, Hampshire (SU 6119), where it was nearly as severe; two people were killed.

### TN1913October27.
### *Dyffryn Dowlais to Bedlinog, Mid Glamorgan (ST 0785 – SO 0901)*

This tornado was so severe that an official investigation was carried out by the Meteorological Office and a detailed report issued as a *Geophysical Memoir* (no.11, by H. Billett, 1914). There are also some excellent photographs of the damage in the *Illustrated London News,* and we have even received two or three letters from eye-witnesses as a result of the TORRO press appeal. The South Wales tornado was one of a number that formed in association with a vigorous thunderstorm cell that was traced from Devon to Lancashire. The first damage was at Duffryn Dowlais, where the tornado was 50 metres wide and damaged outhouses. At Llantwit Fardre trees were uprooted, houses damaged and the top of a dog kennel blown 100 metres. At Treforest the side of the generating station was blown out. At Cilfynydd, where the tornado was said to have been 200 metres wide, corrugated iron sheets were carried a kilometre or more and wrapped round a telegraph pole. The side of a chapel was blown in. Further on, at Abercynon, a row of houses had the roof and joists totally ripped off; a tree was blown 80 metres. The tornado reached its climax at Edwardsville, wrecking a chapel and killing two people. The track here was said to have been 300 metres wide. As with the Lincolnshire tornado of 1667, topography may have been important; the tornado was at its most intense where it was following the deep, narrow Taff Valley.

### TN1931June14.
### *Hollywood, Hereford and Worcester, to Erdington, Birmingham, West Midlands (SP 0877-1191)*

This tornado is described in the *Meteorological Magazine* (July 1931) and *The Times,* with again some good photographs of the damage in the *Illustrated London News.* The TORRO press appeal has brought in nearly 20 letters from eye-witnesses. The track is generally stated to have been from S.W. to N.E. from Sparkhill through Greet, Small Heath, and Bordesley to Erdington, but one appeal letter shows that the tornado had previously reached the ground at Hollywood, just south of Birmingham. Several correspondents compared the damage in the Sparkhill and Small Heath areas to that later seen in the Blitz. Some buildings were completely wrecked, and a woman was killed by a collapsing wall. Photographs show buildings with the whole side blown out. Many houses had to be evacuated

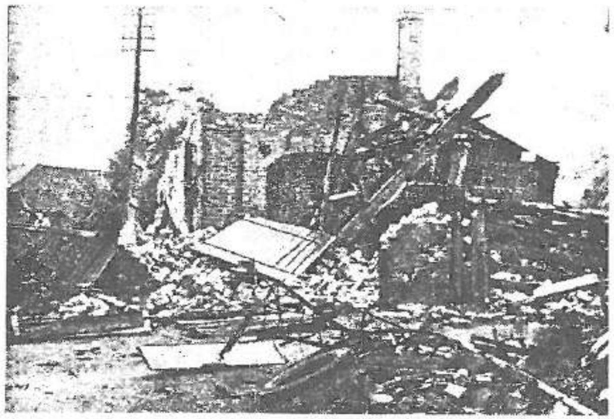


Fig.1: A brick-built blacksmith's forge in South Kelsey (Lincs) destroyed by the T7 tornado of 25th October 1937.

and were later condemned as unsafe. Large trees in Small Heath Park were uprooted and the iron railings round them twisted as if made of thin wire.

TN1937October25. *South Kelsey to North Kelsey, Lincolnshire (TF 0938 – TA 0401)*
This very severe tornado was virtually unknown until 1984, when an eye-witness, Mr. Arthur Knapton, sent TORRO a description, together with a photograph report from the local newspaper. The photographs show that at South Kelsey the tornado was at least force T6, and probably T7. Two brick buildings (a blacksmith's and a joiner's shop) were totally demolished. Also in South Kelsey were a chicken hut and a farm wagon side by side. The hut was blown down the yard and destroyed, while loose straw on the wagon was untouched. In North Kelsey, Mr. Knapton watched as a large tree had its top "twisted off as one would twist the top off a carrot". Given that information on this severe tornado has only recently come to light, it suggests that many other severe tornadoes have yet to be documented.

TN1950May21.
*Wendover, Buckinghamshire, to Heath and Reach, Bedfordshire (SP 8708-9228)*
Like the South Wales tornado of 1913, this one was made the subject of a careful investigation, published as a *Geophysical Memoir* (no.99, by H. H. Lamb, 1957). There are also accounts in *Weather* (July 1950) and the *Meteorological Magazine*, and the TORRO press appeal has produced over a dozen letters about the event. The *Weather* article includes an excellent photograph of the tornado – one of three which occurred in the East Midlands on that date. The tornado was first observed at Wendover, where a correspondent said it looked like the whirlwinds in *The Wizard of Oz*, with bits of building spinning round the top. The tornado then followed the scarp of the Chiltern Hills to Halton (SP 8710), where it lifted the roof of a power station. It then passed on to Aston Clinton (SP 8812), where a correspondent saw it take the roof off the school. At Puttenham (SP 8814) it broke into three or four funnels, but these had coalesced again before it reached Cheddington (SP 9217), where a writer saw "a black spiral cloud coming towards



the village". The worst damage was at Linslade (SP 9024), where two separate columns united into a single tornado about 50 metres wide. A brick bakery was demolished and 50 houses unroofed. The tornado appears to have lifted from the ground again several times, notably at Sutton, near Ely (TL 4479), where roofs were lifted and a house wall sucked out. At Feltwell, Norfolk (TL 7190), dozens of twisting funnel clouds were seen beneath the same storm cell.

TN1954December8. *Chiswick to Southgate, London (TQ 2079-3094)*
This tornado is described in *Weather* and the *Meteorological Magazine* for 1955. Surprisingly enough – it happened in a very densely populated area during the rush hour – only three appeal letters have been received about it. Like the 1913 and 1950 tornadoes, this one was part of a much longer track. The first sign of this tornado was a funnel cloud over the Isle of Wight about 1530 GMT. The storm cell moved N.E. and tornadoes developed from it at Havant (SU 7106) on the Hampshire coast and at Chiddingfold (SU 9635) in Surrey. The main tornado followed a 15km track through Chiswick, Gunnersbury, Acton and Golders Green to Southgate. The track was said to be 400 metres wide. Gunnersbury railway station (TQ 198784) was unroofed, injuring six people. A dozen or more people were injured in Acton (TQ 2080), and a lorry was overturned near Golders Green (TQ 2488). One of the most spectacular incidents occurred in Acton, where a car was seen floating five metres above the ground. The worst damage suggests a strength of TORRO force 7.

SOME OTHER OUTSTANDING TORNADOES OF THE PAST 40 YEARS
This section describes some tornadoes which, although probably not reaching force T6, were nevertheless of exceptional severity for Britain. They appear to be the worst of the known post-1945 tornadoes.

TN1948December13. *Netherton, Dudley, West Midlands (SO 9488)*
Details of this tornado have been discovered only recently, in the archives of the Thunderstorm Census Organisation. The worst damage was the demolition of a garage, injuring the proprietor and an assistant. The roof was lifted off, and two of the brick walls snapped off at ground level. Mr. Jack Wheeler heard "a peculiar sound like a gigantic vacuum cleaner in action" as the tornado approached, and at the same time there was torrential rain with thunder and lightning. Mr. Wheeler then saw half the roof, and the chimney stacks, of a house removed "as if by the hand of a giant". Altogether 47 houses were damaged, some of them severely. The Wolverhampton *Express and Star* of 14th December said that the tornado left "scenes reminiscent of those experienced after an enemy bombing raid".

TN1962January17. *Egremont, Cumbria (NY 0010)*
This tornado occurred about midnight, damaging many houses, 26 of them so severely that they had to be evacuated. A prefabricated house was lifted from its foundations and moved about 10 metres. Again the comparison with bomb damage was used by the local press (Barrow-in-Furness *Evening Mail*, 17th January), which claimed that roofs of prefabs were carried half a mile (about one kilometre). Just over one kilometre S.W. of Egremont, Catgill Hall Farm (NY 002092) was severely damaged. The tornado removed the roofs from all the farm

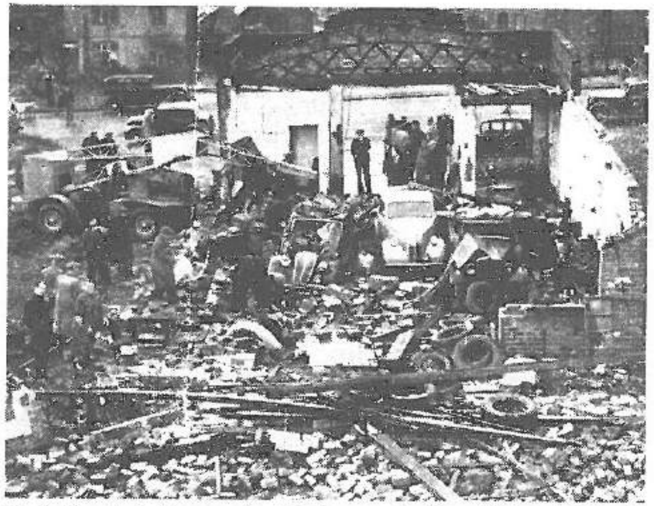


Fig.2: Brookes' Garage in Netherton, Dudley (West Midlands) destroyed by a tornado on 13th December 1948.

buildings. The farmer, Mr. John Braithwaite, saw what appeared to be "a great ball of fire" come straight for the house (*DailyTelegraph,* 18th January).

TN1966October16. *Barton, Oxford (SP 5507)*

A number of prefabricated houses were severely damaged by this tornado. Two of the prefabs were demolished and six damaged so badly that they had to be scrapped. Part of the roof of one was found nearly one mile (over one kilometre away). The tornado funnel was described as "a black cloud 30 yards wide and 200 feet high" and "like a lot of smoke swirling about". The track was from S.W. (*Oxford Mail, Oxford Times,* and site investigations by Dr. Meaden; see *J. Meteorology, 2,* 103-106, 1977, and *8,* 84, 1983).

TN1968April21.

*Wyken, Coventry, West Midlands, to Bulkington, Warwickshire (SP 364807-3985)*

This tornado is described in detail in the TORRO tornado report for 1967-1969. Stables were smashed to pieces and scattered over a 10-acre field; five unoccupied caravans were lifted and thrown; the roof of a caravan was carried 600 metres; a van weighing 0.75 tonne was picked up and dropped on its roof.

TN1978January3. *Newmarket, Suffolk (TL 6463)*

A well-marked cold front brought an outbreak of tornadoes to eastern England, of which the Newmarket one was by far the most severe. Over 100 houses were badly damaged, many losing the roof. Cars were tossed into the air, and a railway signal box was so badly damaged that it had to be demolished. Mrs. Elizabeth Galpin described the tornado as a "great black mushroom". The tornado was well reported by the local and national press. There is some evidence that two (or more) tornadoes occurred in the Newmarket area; the main one, which moved from west to east, had a path up to 200m wide (P. S. J. Buller, *J. Meteorology, 3,* 229-231, 1978).



TN1979June24. *Windsor to Eton Wick, Berkshire (SU 9475-9478)*

In this tornado a 10-tonne lorry was overturned and blown across the road and a one-tonne boat was lifted six metres into the air. At Eton Wick Mr. James Harvey saw "a huge black cone swirling towards us". On the outskirts of Eton Wick a cowshed and dairy were demolished. In another tornado on the same line, at Kings Langley, Hertfordshire (TL 0702), two children were picked up and a wooden chicken house, 40 x 14 metres, was lifted bodily and dropped 70 metres away, totally wrecked. There seem to have been two tornadoes, close together, at Kings Langley; and the Windsor tornado may have split into two before reaching Eton Wick (local and national press; J. M. Heighes, *J. Meteorology, 4,* 233-235, 1979; P. S. J. Buller, *ibid,* 235-240).

TN1982September21. *Bicester, Oxfordshire (SP 5822)*

The "Bicester twister", as the local press inevitably called it, was the most severe of over 20 tornadoes that occurred in England on that date. A workshop lost its roof, which was lifted over the building next door. Another roof was lifted five feet and set down out of position. The most severely damaged building was the Oxfam warehouse in Murdock Road, which partly collapsed. A trailer was lifted over a 10-foot obstacle (*Oxford Mail,* 23rd September; *Oxford Times, Oxford Journal,* 24th September; *Bicester Advertiser,* 29th September; D. M. Elsom, *J. Meteorology, 8,* 141-148, 1983). The strength may possibly have reached T6.

## THE GREATEST MULTIPLE OUTBREAKS

Multiple outbreaks were first described (for Britain) by Lacy in his important article in *Weather* for March 1968. We now know of 10 days which had at least 10 tornadoes each. Dr. Meaden's accompanying article on whirlwind classification gives the eight undoubted cases since 1960; there was one much earlier instance known to TORRO (1870 October 19th), and the outbreak of 1978 January 3rd probably also had over 10 tornadoes. Dr. Meaden's article discusses the conditions in which such large outbreaks occur. The present paper gives brief details of the largest outbreaks.

*1870 October 19:* These tornadoes, which probably broke out on a cold front, occurred mainly in S.W. England, but there were some as far east as Saffron Walden, Essex (TL 5438), and as far north as Stratford-upon-Avon, Warwickshire (SP 2055). The outbreak is known mainly from letters to *The Times* and the *Meteorological Magazine.*

*1966 November 15:* Tornadoes broke out on a vigorous cold front crossing England and Wales from the N.W. The tornadoes were in northern England, the Midlands and East Anglia. The worst damage was at Leicester (SK 6004), where a well-built school building partly collapsed, injuring 24 pupils; hundreds of houses were damaged (*J. Meteorology, U.K.,* vol.8, pp.85-87, 1983).

*1966 December 1:* An extremely deep depression (943mb) crossed Northern Ireland and Scotland; tornadoes broke out in many areas of England and Wales, especially in the S.W. counties and the S.E. Midlands. The most severe damage was at Bridgwater, Somerset (ST 3037), Biggleswade, Bedfordshire (TL 1945) and Gamlingay, Cambridgeshire (TL 2452) (*ibid.,* pp.86-88).

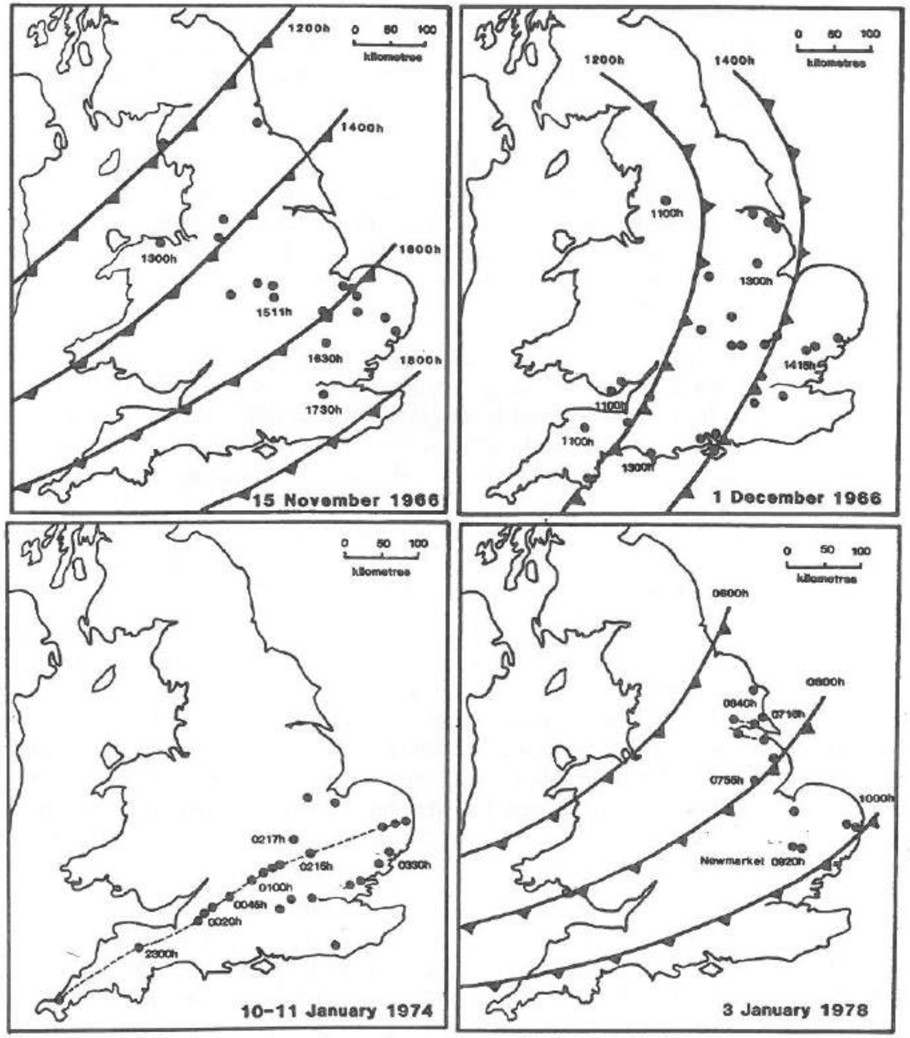



Fig.3: Locations of tornadoes in four multiple tornado outbreaks.

*1971 December 19th* Most of these tornadoes broke out in a band running from Devon to Bedfordshire; there were also a few cases on and near the south coast of England. Some of the worst damage was to farm buildings at Lower Wanborough, Wiltshire (SU 2082).

*1974 January 10th-11th:* An exceptionally deep low, 934mb, lay to the west of Scotland, and a thundery trough crossed the country during the night. The tornadoes occurred on the trough in a zone from Devon to East Anglia, the distribution pattern being rather similar to that in the 1971 case.



*1978 January 3rd:* These tornadoes formed on a vigorous cold front. They were almost all in Humberside and Lincolnshire, with two isolated examples in East Anglia (one of these, at Newmarket, Suffolk (TL 6363), may have been of force T6).

*1981 October 20th:* Another well-marked cold front produced numerous tornadoes in a comparatively small area from Somerset to West Kent. 31 tornadoes are known for this day.

*1982 September 21st:* The Midlands and East Anglia suffered from this outbreak, which was on the cold front of a low north of Scotland; ex-hurricane Debby formed a secondary low on this front. By far the worst damage was at Bicester, Oxfordshire (SP 5823) (*J. Meteorology*, vol.8, pp.141-151, 1983).

*1984 February 8th:* A thundery cold front swept rapidly across the country, with tornadoes in a band from North Wales to London (D. M. Elsom, *J. Meteorology*, vol.10, pp.4-15, 1985).

I have left the outbreak of *1981 November 23rd* for more detailed treatment, since it was by far the most outstanding case so far recorded. The number of tornadoes that day exceeded the next four largest outbreaks put together; it also

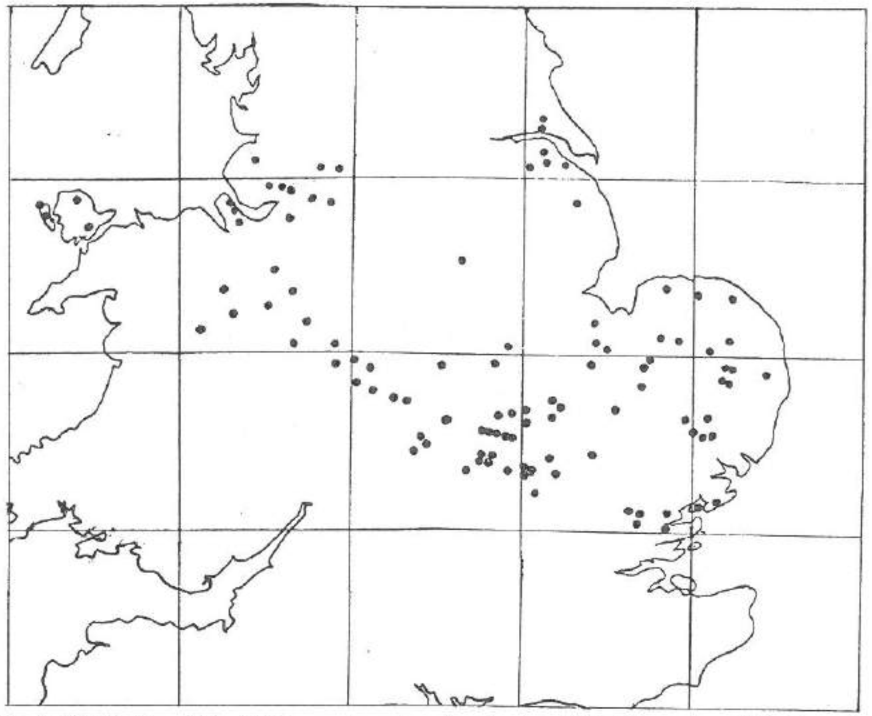


Fig.4: Distribution of the 105 known tornadoes for the day of 23rd November 1981, Europe's biggest outbreak on record. The tornadoes were associated with a line-squall cold front which crossed the country from N.W./W.N.W. during a period of under six hours.

exceeded the previous British record for an entire year (84 in 1974). The 105 known tornadoes broke out on a well-marked cold front associated with a small secondary low.

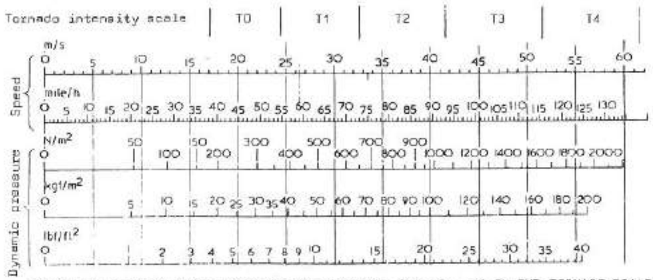
The first tornado on this date, or rather two tornadoes, struck Holyhead, Anglesey (SH 2482), about 1030 GMT, damaging 20 houses and ripping half the roof from a school building. There were several tornadoes on Anglesey; one, at Amlwch (SH 4392), lifted and overturned a summerhouse which was screwed to a concrete base. The owner had thought the tornado roar was an approaching train; many other correspondents compared the sound of the tornadoes to that of an express train or a low-flying aircraft.

The next area to be struck was Merseyside and Greater Manchester. At Croft (SJ 6393), near Warrington, it was claimed that fences were hurled up to a mile (nearly two kilometres). At Newton-le-Willows (SJ 5894) iron gates were torn off and mangled. Further south, in Shropshire, a man at Market Drayton (SJ 6734) saw multiple funnel clouds – "two gigantic hands of low cloud, with fingers outstretched".

It was lunchtime when the outbreak reached the Birmingham area. Severe damage was done at Dudley (SO 9390) and at Rushall (SK 0201), near Wolverhampton. At Stoneleigh (SP 3272), south of Coventry, a metal tractor garage was blown down and large trees were uprooted, or had their branches pulled up like an umbrella.

The density of tornadoes seems to have been highest in the East Midlands and East Anglia. The Northamptonshire newspaper published spectacular photos of caravans damaged at Cosgrove Lodge Park (SP 7942): seven were destroyed and four thrown into a lake. In Huntingdon (TL 2371) 50 houses were badly damaged, some having the roof ripped off. The small county of Bedfordshire alone had 10 known tornadoes; Norfolk had 13, but in a much larger area. The last tornadoes broke out in S.E. Essex shortly before 1600 GMT.

The reason why this outbreak appears so outstanding is certainly the fact that it was investigated particularly thoroughly. 'Only' about 35 tornadoes came to light through the press-cutting agencies – normally TORRO's main source of reports. An appeal by Michael Hunt on Anglia Television produced another 30. Most of the other reports were received as a result of a special appeal for information in a large number of provincial newspapers. If similar appeals had been made at the time of other large outbreaks, it is likely that many of them would have been credited with far more cases.




RELATIONS BETWEEN WIND-SPEED, DYNAMIC PRESSURE, AND T0 – T4 ON THE TORNADO SCALE



# STRUCTURAL DAMAGE CAUSED BY TORNADOES IN THE UNITED KINGDOM

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*Abstract:* This paper reports on the damage caused to buildings and other structures by tornadoes in the United Kingdom. The information has been collected from press cuttings, supplemented with site visits, for the period 1962-1984. Details of the types of damage that occur and typical costs of repair to houses are included. The degree of damage, related to the severity of a tornado, and details of personal injuries, are assessed in comparison to the overall situation arising from severe gales and storm.

## INTRODUCTION

During the early 1960's the Building Research Establishment (BRE) started an extensive programme of research into the effects of high winds on both high-rise and low-rise structures. To complement this work, an investigation into the types and scale of gale damage to buildings was also initiated. Very few records of damage were available; the insurance companies tended to lump all types of storm damage together, from which it was not possible to extract the records of gale damage alone, and local authorities only kept separate records following unusual wind events – and then only for their own properties. A detailed study of press reports of damage was therefore started in 1962 and is continuing. It was envisaged that this study would be backed up with site investigations in the event of particularly severe winds which caused large amounts of damage. At that time tornadoes and their effects on buildings and structures were not specifically considered.

The growing collection of newspaper cuttings soon came to the attention of R. E. Lacy, a member of the B.R.E. staff engaged in the study of building climatology. As a meteorologist he became interested in the not infrequent references to 'whirlwinds', 'freak gusts' and other unusual events. Using the meteorological data available and following this up with letters and site visits he soon determined that many of these unusual events were tornadoes. During the period 1963-66 inclusive he found evidence of 78 tornadoes, at that time a figure which was considered a surprisingly large number.

Although Lacy undertook no further surveys his report[1] led to the realisation that tornadoes were not freak events that occurred only rarely in the United Kingdom. Furthermore, it was also realised that, during a tornado, it was possible for large numbers of buildings to be exposed to wind speeds that were estimated to equal or exceed the once in 50 years return period gust speeds used in building design. These buildings would, of course, be in a well defined area, so site surveys of damage would be worth considering.

Since then a number of tornado incidents have been the subject of site investigations and reports published. These visits are best carried out within a day or two of the event; damage is quickly covered or repaired, and people tend to forget, and subsequently exaggerate, exactly what happened.

## DAMAGE

It still causes considerable astonishment to most people that the United Kingdom experiences tornadoes, let alone that they might cause damage. The B.R.E. survey has shown that, on the basis of its records of damaged buildings during the 15 years up to and including 1984, each year on average there were 11 days on which known tornadoes *caused damage to buildings.* On each tornado day the number of sites (individual towns or villages) in which damage occurs varies greatly, as does the number of tornadoes causing the damage. Fortunately the scale of damage caused in the U.K. is far less severe than that experienced in countries such as the U.S.A.

The less severe tornadoes cause minor roof damage (usually no more than the removal of a few roof tiles) and somewhat more damage to sheds, other less well constructed buildings, buildings which have deteriorated, and garden walls and fences. A certain amount of indirect damage to property is also caused by wind-borne debris or falling trees and branches. The gust speeds experienced during these smaller events are generally below the once-in-50 years return-period gust-speeds used in the structural design of buildings.

The more severe tornadoes produce gust speeds which exceed the 50-year design value and damage is correspondingly worse. In the case of houses, chimneys are frequently toppled and roofs stripped of tiles. Timber roof structures are often damaged or even moved on the house walls, and gable-end walls are sucked out. Less well-constructed buildings such as garages or conservatories may be completely blown over. Sheds and greenhouses may be blown over, lifted off their foundations, or even carried considerable distances in the vortex before being dropped. It is this lifting action of tornadoes which produces the extremely large amount of indirect damage which is so characteristic of these events. The rotating core tends to pick up debris such as tiles, roofing sheets, pieces of fencing or even complete garden sheds. When dropped, this debris causes further damage to roofs, cladding and windows, often generating even more debris.

Industrial buildings lose sheeting from roofs and walls, the less well-built buildings sometimes losing the whole roof structure complete with its covering. Indirect damage can be particularly severe when it involves buildings clad and roofed with a brittle material such as asbestos cement sheeting.

One form of damage mechansim often referred to in tornado literature is the 'explosive' failure of buildings within the eye of the tornado. The static pressure within the eye is lower that that of the surrounding air and it is suggested that the sudden drop causes the building to explode. The author is certain that this is possible, but site surveys carried out have so far in the United Kingdom revealed no direct evidence of this kind of failure. It is felt that many of the instances reported are due to a genuine misunderstanding of the way in which wind forces act on buildings. The wind causes direct positive pressures on the external windward face of a building, but by far the greatest forces arise from suction forces acting on flat or low-pitched roofs, or on the walls at corners of buildings, the suctions being caused by accelerated air flows in these areas. Although the positive pressures can produce failures, the majority of damage is caused by outward acting forces which are combinations of the positive internal pressure of the building and the external suction (which is usually considerably larger in magnitude). Thus the usual failure mechanism is for wall components to be sucked from the building and roofing to be lifted off – the end result giving the appearance of an explosive failure. A former colleague now working in this field in the U.S.A. has confirmed instances of similar misinterpretation of damage.



It is extremely difficult to estimate the wind speeds which cause such damage. Tornado intensity scales are related to wind speed but rely on visual inspection of damage to both buildings and trees to determine scale intensity. But buildings vary considerably in design, soundness of construction and maintenance, and can have varying amounts of shelter from other buildings depending on the direction of air flow. Often what appears to be extensive damage could have been caused by comparatively low wind speeds. This is often the case with non-engineered structures; an investigation at Winslow, Buckinghamshire in 1981[2] revealed an entire roof lifted off a farm building that depended solely on its own dead weight to stay on. Calculations showed that a gust speed of only 17.5m/s could create enough uplift on the roof to overcome its dead weight. Although calculations of this kind need to be used with caution, they can give a good approximation of the minimum speed needed to generate certain damage.

When the Electrical Research Association buildings at Cranfield in Bedfordshire were damaged in 1973[3] there was a standard Munro anemometer mounted on a mast nearby. Unfortunately this was not quite on the direct track of the tornado but it did record a gust of 38m/s, only 2m/s less than the design gust speed for that area. The main damage, based on the TORRO scale,[4] indicated a gust speed of some 37-55m/s

More recently during the Teignmouth tornado in 1984[5] four large chimney stacks were toppled. Calculation showed that a gust of some 62.5m/s would be necessary for this, well above the design gust speed of 43m/s for that part of the country.

It should also be remembered that wind speeds are not uniform across the width of the tornado path. The speed of advance of the tornado needs to be added to the speed of rotation and, as tornadoes in the U.K. generally rotate in an anti-clockwise direction when viewed from above, this means that the right hand edge of the damage path experiences the highest speeds.

## DAMAGE COSTS

An important part of the overall gale damage survey is to produce estimates of the cost as well as the quantity of damage. Each year on average gales in the United Kingdom damage at least 200,000 structures at a cost of some £35,000,000 (1984 prices). But these estimates, in particular the number of buildings damaged, are certainly low. Newspapers always concentrate on the more spectacular damage and tend to ignore minor incidents.

Tornadoes tend to attract press coverage and over the last eight years the number of occurrences of tornado damage has been 20% of all gale damage. (An occurrence is just one damage incident – a chimney blown down for example, or a roof damaged). However, because so much ordinary gale damage does not get picked up by the survey, it would be wrong to suggest that tornadoes account for 20% of all damage and damage costs, especially as a large proportion of the £35,000,000 annual figure is caused by a few major incidents – such as the collapse of a cooling tower.

In a recent paper on building performances in this country[6] it was demonstrated that nearly 75% of all gale damage occurs during large 'storm' events – there were only three of these in the 20-year period up to and including 1983. A further 16% occurs throughout the year as 'background' damage. This is mostly damage which occurs at wind speeds well below design speeds, due to errors in design or construction and the deterioration of older buildings. The remaining 9-10% was attributed to tornadoes. Even this is probably an overestimate and because of this low percentage and the random nature and confined area of these events, tornado wind speeds are not incorporated into the data used as a basis for the design of normal buildings.

Probably the best sources of damage costs to domestic properties are the Grantham and Gotham tornadoes that occurred in October 1977 and August 1984 respectively. In both cases the tornadoes passed through housing estates which belonged wholly, or in greater part, to local authorities.

In the most recent at Gotham, Nottinghamshire last August, 94 houses were damaged. Estimates of repair costs given by early eye-witnesses were in the order of £200,000, and this value was widely reported in the press. This seems to have been based mainly on the overall picture of debris-littered streets rather than a careful look at the damage. It proved to be a considerable overestimate. In fact the 74 council-owned houses were repaired at a total cost of £50,000, an average of £676/house.[7] The labour costs for these repairs varied from only a few pounds up to a maximum of £1,000/house. The council also repaired ten of the privately owned dwellings and the remaining ten were repaired privately. Assuming that the damage to these was on a pro rata basis then the repairs to 94 houses cost slightly more than £63,500. There was also £12,000 worth of repairs to blocks of garages, most of which had lost their asbestos roofs and some had had their brick walls blown down.

At Grantham, Lincolnshire in 1977, 60 houses were damaged at a total cost of £16,575 an average of £276/house (1984 prices). The damage indicated an intensity of 2 on the TORRO scale. Outside the town several isolated properties were more seriously damaged; 11 at a total cost of £48,705, an average of £4,428/property, intensity 3/4 on the TORRO scale.

This latter figure for the cost of damage, agrees quite well with the value quoted by Lamb following damage at Linslade, Buckinghamshire in 1950.[8] 50 houses were severely damaged and a bakery demolished at a cost of at least £237,250, (approximately £4,650/property) in what has since been classified as a force 6 event. The only illustration of building damage in Lamb's report does show a great deal of damage – whole roof structures removed and brick walls partially demolished, but most of this appears to be fairly old property which could have been weakened by deterioration following the Second World War and the ensuing years.

The one other cost of tornado damage is that caused by the collapse of buildings on to people. In the period 1962-84 no deaths were known to us that were directly attributable to tornado damage to *buildings*. The injuries from tornadoes, recorded in Table 1, total 8 major and 124 minor instances – injuries are considered major if they entail a stay in hospital. The total includes injuries caused by being blown over by the wind – although this does not involve building failures, very often the high gusts responsible are caused by buildings which have modified the local wind environment due to their shape and height. The overall gale damage casualties for the same period are 113 deaths, 197 major and 1,618 minor injuries. So tornado



Table 1: Injuries known to be directly associated with tornado damage to *buildings* (according to the B.R.E. press-cutting files). 1962-1984.

| | *Injuries* | | | |
|---|---|---|---|---|
| | *Major* | *Minor* | *Combined* | *As % of Total* |
| FALLING ARTICLES | | | | |
| Chimney pot | | 1 | 1 | 0.8 |
| Tile/slate | | 4 | 4 | 3.0 |
| Asbestos roofing | | 9 | 9 | 6.8 |
| Glass roofing | | 1 | 1 | 0.8 |
| Unspecified roofing | | 1 | 1 | 0.8 |
| Bricks and rubble | 6 | 20 | 26 | 19.6 |
| Boundary walls | | 4 | 4 | 3.0 |
| Hoardings | | 3 | 3 | 2.3 |
| Scaffolding | | 2 | 2 | 1.5 |
| Glass | | 10 | 10 | 7.6 |
| Glass (generated by other debris) | | 4 | 4 | 3.0 |
| Unspecified debris | 1 | 5 | 6 | 4.6 |
| COLLAPSING/OVERTURNING | | | | |
| Shed | | 3 | 3 | 2.3 |
| Greenhouse | | 1 | 1 | 0.8 |
| Marquee | | 1 | 1 | 0.8 |
| Caravan | 1 | 34 | 35 | 26.4 |
| OTHERS | | | | |
| Blown over | | 7 | 7 | 5.3 |
| Hurt digging out another victim | | 1 | 1 | 0.8 |
| No details | | 13 | 13 | 9.8 |
| TOTALS | 8 | 124 | 132 | 100.0 |

damage accounted for 4.1% of all major injuries and 7.7% of all minor injuries. The greatest single cause of injury during tornadoes was to people whose caravans were destroyed; but two-thirds of these occurred in only two events when large caravan sites were hit so this is probably not statistically significant. Many injuries were of a very minor nature and were caused by falling or wind-borne debris. In view of the large amounts of debris that a tornado core can accumulate it is perhaps surprising that more injuries have not been recorded.

## CONCLUSIONS

This paper has reported on the damage caused to buildings and other structures by tornadoes in the United Kingdom. The information has been collected from press cuttings supplemented with site visits. The severity and cost of the damage is often exaggerated in press reports. This is perhaps a natural reaction; we are used neither to seeing many buildings damaged in a small area nor to seeing the streets littered with large amounts of debris.

In the smaller tornadoes the wind speeds are below those used in structural design, and much of the damage, especially in the case of new building, could have been avoided with a little extra care in detailing at both the design and construction stage. Repair costs vary, but can be averaged at a figure up to about £1,000/house.

In more severe events the wind speeds can be *well above* the design values and more damage is inevitable. Damage costs will run into many thousands of pounds.

The lower rate of occurrence of tornadoes in the United Kingdom compared with other wind events and the limited area affected by each one, argue against taking them into account when formulating the basic wind speed used for the design of conventional buildings. The design of certain buildings and structures of an important or sensitive nature is another matter, and would require special consideration.

ACKNOWLEDGEMENTS

The information in this paper has been obtained as part of the programme of research of the Building Research Establishment of the Department of the Environment. This paper is published by permission of the Director.

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Severe damage in west London caused by the T7 tornado of 8th December 1954, *Acton Gazette,* (see also photograph on p.211).



# THE SPATIAL AND TEMPORAL DISTRIBUTION OF BRITISH THUNDERSTORMS

By BOB PRICHARD
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*Abstract:* It is urged in this paper that increased consideration should be given to the geographical aspects of thunderstorm occurrences in Britain. In this context, a new statistic 'days of overhead (or close) thunderstorm' is suggested which would reduce some of the problems encountered with the use of the present statistic 'days of thunder heard'.

Much research has gone into the physics of thunderstorms, but much less into their geographical distribution. This note suggests ways of redressing the balance. Given broad-scale meteorological conditions favouring thunderstorms, why should certain areas be more prone to storms than others – and can we predict which those areas will be?

We can tackle this study in two ways. One is to use maps of the average number of days with thunder heard per month or year. This may show us the regions that experience most and least thunder (Fig.1). The second approach is to study thunderstorm reports as received on particular days, and see if particular areas experience thunder regularly under certain synoptic conditions – or, conversely, if they miss them. The reader is referred to the December 1984 issue of the *Journal of Meteorology* for more detail on the reporting and collection of such data.

## DAYS OF THUNDER HEARD

This is one of the most difficult meteorological statistics to handle. The more conscientious observer in quiet surroundings may hear a rumble of thunder as far as 25km from him. Conversely, some people may not hear thunder that is as near as 5km. This can clearly make a mockery of any attempt to discover which parts of the country have the most thunder. Additionally, if there are preferred thunderstorm tracks it may well be that there are places lying mid-way between two such tracks that will hear a lot of thunder from the distant storms, but experience few overhead storms.

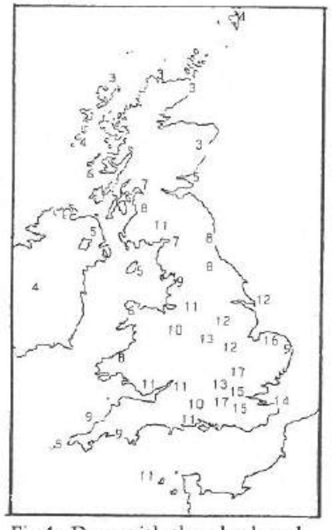

Fig.1: Days with thunder heard per year, based on 1971-1980 figures (mostly Meteorological Office stations).

It is, therefore, suggested that we investigate whether a new statistic 'days of overhead (or close) thunderstorm' is practicable to supplement 'days of thunder heard'. The Thunderstorm Census Organisation attempted to draw this distinction in their reports in the 1930's, and this author recalls chatting to the observer at the (now closed) Southend Climatological Station who maintained that he only reported thunder when it was 'nearby'. Certainly, it would call for some judgement, but a definition such as given in an article by Benford (*J. Meteorology,* vol.5, no.51, p.213) should not be too difficult: "a day of (overhead) thunderstorm' is one

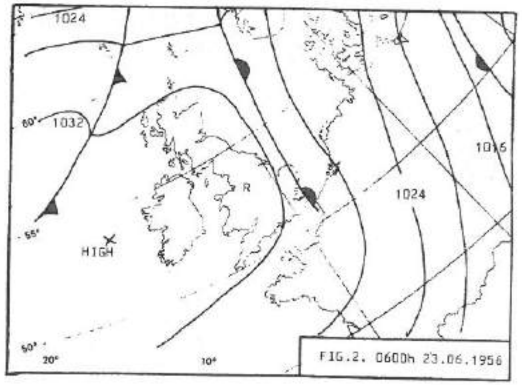


Fig.2:

Weather map for 0600 on 23rd June 1956.

Thunder was heard at Ringway ("R" on the map) in the early afternoon; then, between 1745 and 1830h GMT there was a thunderstorm giving 6.8mm of rain and hail. The storm seems to have been triggered by high ground to the north of Manchester, and there may have been a weakness in the upper flow on the western edge of an upper trough over Europe.

on which an ordinary person, going about his daily business is aware of thunder – given that that person is not in a sound-proofed room or surrounded by considerable noise". In any event, it is suggested that the problems of judgement would not result in any greater difficulties than 'days of thunder heard' creates when it comes to analysis.

## THUNDERSTORM REPORTS

It is the more isolated thunderstorms which make the most interesting study when it comes to studying the geography of the subject. By their very nature, though, such reports need careful scrutiny. Observers are liable to credit storms to the wrong date, or give 'a.m.' instead of 'p.m.' and vice versa. A solitary report for any day must always be suspect – and yet storms do occur on the most unlikely of days. Consider, as an example, the quiet synoptic situation shown in the weather map in Fig.2. Rather unexpectedly, thunder was heard at Ringway, Manchester ("R" on the map) in the early afternoon; then, between 1745 and 1830 GMT there was a thunderstorm giving 6.8mm of rain and hail. Many hailstones were over 5mm in diameter, and some as thick as 12mm. In this case, the storm seems to have been triggered by high ground to the north of Manchester, and there may have been a weakness in the upper flow on the western edge of an upper trough over the Continent.

Obviously, we do need more thunderstorm observers so that solitary reports can be corroborated or rejected. There is a clear role here for all those people interested in the weather.

In Fig.3 the satellite images show examples of showers and isolated thunderstorms.

## CURRENT STATE OF KNOWLEDGE

There is still much to learn. The role of sea-breeze fronts and heat islands in triggering off thunderstorms needs further study, as does the effect of high ground and coastal terrain. On the synoptic scale, the role of weak fronts in summer is not always appreciated; cloud may break in their vicinity, allowing the temperature to rise, and this may release latent instability. Many is the weak summer cold front that has suddenly come to life in this way (see Fig.4 for example).



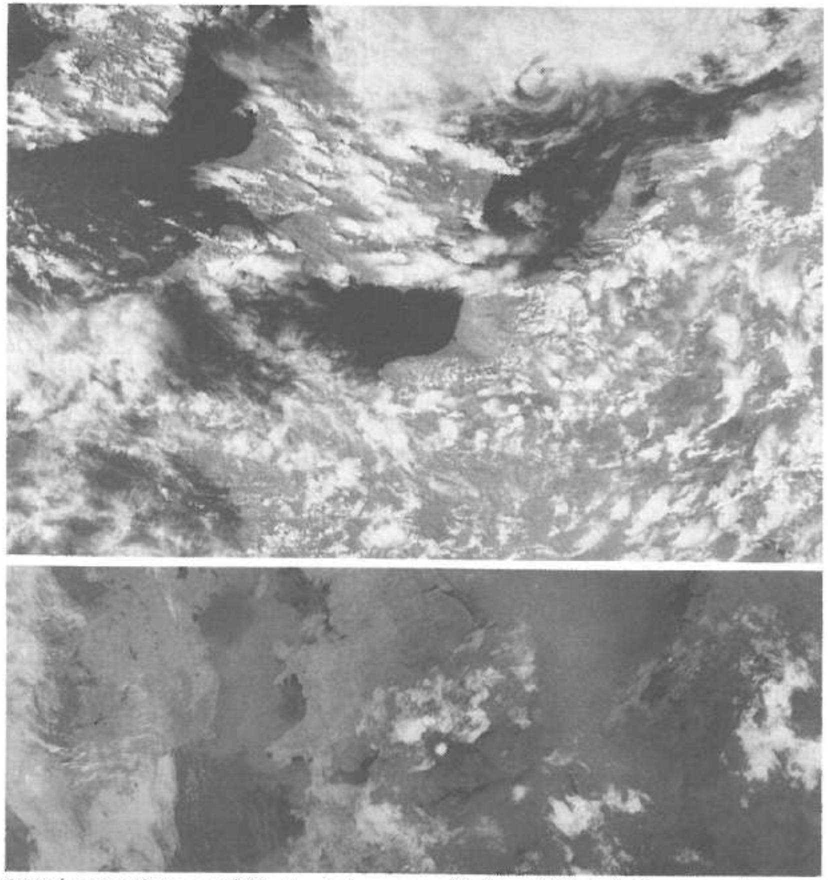

Fig.3: (Lower photograph). Scattered showers on 8th June 1982, including a prominent one over the Thames Valley; (Upper photograph), showers over Ireland, southern Britain, northern France and the Low Countries on 12th June 1982 at 1414 GMT (NOAA 7 photographs by courtesy of the University of Dundee Electronics Laboratory).

As a starting-point, the figures which we have suggested that the places with most thunder on an annual basis are likely to be (i) inland (from prevailing winds), and/or (ii) near high ground and/or (iii) near large towns.

## DIURNAL DISTRIBUTION

Davis (1969) and Prichard (1973) have produced studies showing the times of day most prone to thunder for Heathrow and Ringway Airports respectively. These showed late afternoon as the peak time, with a secondary peak shortly after midnight at Heathrow. By contrast, Shone's results for the south-west coastal location of St. Mawgan, Cornwall (Fig.5) showed a thunderstorm maximum between 1800 and 0100 GMT (Shone 1977). Further studies would be useful for other parts of the country so that maps could be built up showing such distributions.

It is usually, but not always, reported to have been observed during a thunderstorm (89%), often one of exceptional violence (41%). If not seen during a thunderstorm, conditions may be described often as 'thundery' or 'sultry', suggesting a trend towards foul-weather electric-field intensities. In about a third of cases, observers did *not* report that the ball lightning was formed after a lightning flash. In about a fifth of cases, BL was said to have formed within 30 seconds of a flash, usually a cloud-to-ground flash. In a few only (7%) was the BL seen to form within 10 metres of the point of impact of the flash.

Although no such observations were recorded in the present survey, it is reported in the literature that ball lightning and similar luminous phenomena have also been associated with other extreme atmospheric conditions such as tornadoes, or unusual geophysical events such as earthquakes or eruptions of volcanoes.[15]

About 90% of BL are spheroidal. Predominant colours are orange-yellow or white. The diameter of BL follows a log-normal frequency-distribution with a median in the range 25cm. The present survey also showed a log-normal frequency-distribution for duration of the events, with median about 5 seconds. Both these distributions may result from psychological factors relating to perception and memory. There was no correlation between diameter and duration.

BL seen at close quarters may appear to have a structure such as a translucent halo around an opaque core. A similar effect sometimes described is 'limb-darkening'. At such close range, rotation is sometimes observed.

Usually, BL is a singular phenomenon, but occasionally several are seen together or it may divide into parts. Usually, it has a brightness similar to that of a 40 W tungsten lamp, and like other aspects of its appearance, this remains relatively constant throughout its lifetime. About half the observers report predominantly horizontal motion, which may suggest that BL has a mass-density about the same as that of atmospheric air.

In more than half the cases, observers reported that BL made contact with a solid object, but this was usually only surface contact. Sometimes the BL was seen to bounce from a solid surface. Occasionally, this contact seemed to bring about the end of the ball. There was no apparent difference in the behaviour of the ball when in contact with conductors or dielectrics.

Only a few observers reported a sensation of heat, and this was either when the BL made contact with them or was within 10cm of them. Occasionally the BL was said to have singed fabric, wallpaper or grass, or to have caused other thermal damage. A small number of observers reported odours, which, if they were not the smell of burning caused by the ball lightning, were described as 'ozone', 'oxides of nitrogen', or specifically, 'nitric oxide'. About 20% of observers described sounds from the BL before the end of the event. Sometimes, the initial appearance of the BL was associated with a loud, sharp report. Sometimes, within 5 metres distance, rattling or crackling sounds were heard. Most often, when sounds were heard, these were a fizzing or hissing sound – audible even at 20 metres distance. This sound probably did not originate from the BL itself, but was from nearby coronal point discharge, which suggests ambient electric field intensities of about 1.5 to 3 $kVm^{-1}$ compared with the fair-weather field of about 130 $Vm^{-1}$

Occasionally, the BL emitted sparks or lightning, or had halos, coronas or protrusions.



Although about 25% of the cases were associated with traces or damage, in all but 10% of the events this damage could be attributed to ordinary lightning. In those cases where such an interpretation did not seem possible, BL was reported to have (i) burned a small hole in polyester fabric, (ii) burned a 1cm wide strip in (ceramic?) tiling, (iii) scorched the walls of a room, burned some picture glass and broken a window, (iv) scorched grass, and (v) damaged iron gutters and a chimney. With the exception of (iv), the damage caused by BL does not seem to be severe. From such cases, James Barry[7] has estimated the energy density of ball lightning, and found that, like the frequency distributions for durations and diameters described above, energy density follows a log-normal frequency distribution with median about 1 $Jcm^{-3}$

BL seen in enclosures most often ends while in contact with a solid object, whereas a greater proportion of those seen out-of-doors end in mid-air. The decay of BL was described as silent in 30% of cases. Just under 10% of observers reported a subdued explosion, sometimes described as like the bursting of a balloon or blown-up paper bag. Just over 60% reported an explosive decay, which might in some cases have been the simultaneous thunder from a nearby lightning flash.

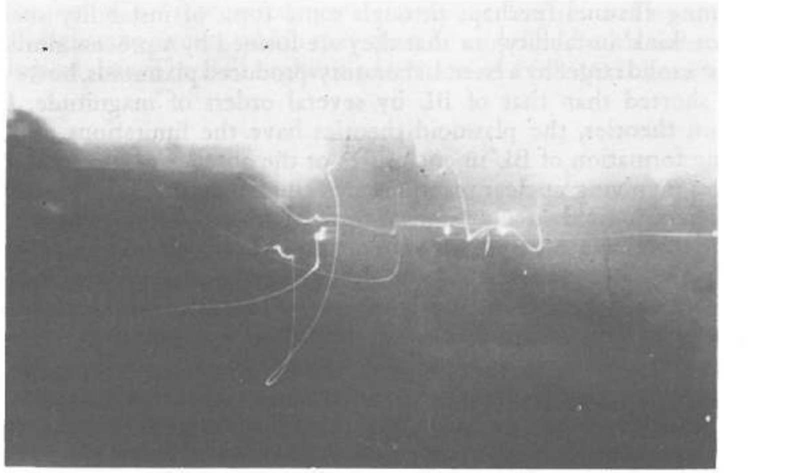

Fig.1: Time exposure taken by a physicist, Mr. W. T. Cowhig, at Rugby during a violent thunderstorm in 1937 or 1938 showing anomalous trace interpreted by the photographer as having been caused by ball lightning, although he himself did not see ball lightning.

## BALL LIGHTNING THEORIES

Ball lightning theories conveniently fall into two categories: (i) those in which the ball lightning is self-contained with its own *internal energy source,* and (ii) those in which the BL receives a steady supply of energy from outside, i.e., from an *external energy source.* The first group of theories attempts to explain the independent mobility of ball lightning and its apparent lack of dependency on electrical conductors for its prolongation. The second group attempts to account for the long, steady luminosity of BL, whose duration exceeds that of ordinary lightning by several order of magnitude.

The internal energy-source models most often discussed in the literature include those based on combustion or chemical reactions, plasmoids (self-contained elements of plasma) and nuclear reactions.

Combustion and chemical theories are usually based on the initiation of burning of inflammable materials or gases (such as methane), or of exothermic reactions (involving ozone or oxides of nitrogen), by contact of the lightning channel with the ground or solid objects, or by coronal discharge. These theories suffer several limitations; firstly, they suggest that convection of the hot gas would be observed, whereas the motion of BL is predominantly horizontal. Secondly, they do not offer a convincing explanation for the formation of a spherical structure of constant diameter and luminosity and with a lifetime of several seconds. Thirdly, these theories do not account for BL formed inside enclosures such as rooms.[8]

Plasmoid theories are based on the hypothesis, which has received some experimental support, that fluid motion of an element of plasma in the form, say, of a vortex ring could produce its own, self-containing magnetic field. The proposed formation mechanism for such plasmoids is either a detachment or ejection from the lightning channel (perhaps through some form of instability such as the 'sausage' or 'kink' instability), or that they are formed by a process similar to the ablation of a solid target by a laser. Laboratory-produced plasmoids, however, have lifetimes shorted than that of BL by several orders of magnitude. Like the combustion theories, the plasmoid theories have the limitations of failing to explain the formation of BL in enclosures or the absence of convection.[9]

Theories involving nuclear reactions are founded on the suggestion that high values of electric field encountered in thunderstorms could accelerate charged particles to the kinetic energies necessary to initiate nuclear reactions. This would suggest that BL would be radioactive, although there is very little evidence that this is so. Indeed, no cases have been reported in which BL observers have suffered the effect of ionizing radiation, even at very close proximity.[10]

Perhaps the most obvious single discrepancy between observations and the theories outlined above is that the theories would mostly seem to require that ball lightning be formed directly as a result of a lightning strike to the ground and would therefore be observed in the immediate vicinity of the point of impact. This is not confirmed by more than a very small minority of observers. The above theories fail to explain ball lightning formed inside enclosures, BL observed in the absence of ordinary lightning, or the constancy of diameter and luminosity.

The external energy-source models, irrespective of their merit as physical theories, appear to receive more support from the observations studied than do the internal energy models.

Kapitsa[12] proposed an interesting theory in which ball lightning was formed by standing waves of natural radio frequency radiation emitted by natural lightning. However, such emissions in the appropriate part of the r.f. spectrum have been shown to be too weak to enable such a process to occur.[12] Recently, a rare but highly energetic form of lightning discharge, called a 'lightning superbolt', has been discovered. The existence of natural lightning of exceptional energy and extended duration may offer new hope for theories such as Kapitsa's.[13]



Several theories have been published based on electrostatic discharge.[14] These would suggest that ball lightning is a phenomenon closely related to St. Elmo's fire. There was a reasonable amount of circumstantial evidence found in the observations studied to suggest that these theories were most consistent with observations. Several observations described the formation or decay of BL while in contact with an electrical conductor; others described formation or decay associated with a lightning flash, thus suggesting a sudden change in local electric field intensity. The odours and sounds described by many observers, and the absence of any dramatic heating effect, offer further evidence for discharge theories.

## CONCLUSIONS

It has been shown that many published theories of ball lightning do not receive strong support from the descriptions of eyewitnesses. In this survey, theories based on electrostatic discharge seemed to be most nearly consistent with the accounts of observers.

However, there is a serious limit on the quantity of useful information which may be derived from anecdotal descriptions of events observed, perhaps, many years in the past. What is required now is the rapid collection and investigation of recent ball lightning events which may then be correlated with more objective meteorological data. The Ball Lightning Division of TORRO is soon to attempt this.

### NOTES

1. See Uman (1969).
2. See Golde (1977).
3. "The term *ball lightning* has been applied to the singular, luminous, persistent and relatively small globular mass occasionally observed in the atmosphere and associated with thunderstorms and natural lightning." (Barry, 1980).
4. "Lightning can be defined as a transient, high-current electric discharge whose path length is generally measured in kilometres. Lightning occurs when some region of the atmosphere attains an electric charge sufficiently large that the electric field associated with the charge causes electrical breakdown of the air." (Uman, 1969).
5. See Stenhoff (1976), Wooding (1976).
6. "St. Elmo's fire is a relatively common luminous globe formed by a corona discharge from a pointed object in the ground such as a stake. It appears when the atmospheric electric field is intensified, as it is during a storm. In unusually high fields, which often occur on mountain peaks, this form of discharge may be seen on any protrusion above the ground, even on the hands and heads of people . . ." *(Singer, 1971).*
   The chief observed difference between St. Elmo's fire and ball lightning is the inability of the former to become detached from an electrical conductor.
7. See Barry (1980), pp.46-70.
8. See Singer (1971), pp.81-88; Barry (1980), Ch.7.
9. See Singer (1971), pp.114-133; Singer, S. "Ball Lightning", in Golde (1977) pp.423-425.
10. See Singer (1971), p.88; Singer, S. "Ball Lightning", in Golde (1977) pp.425-427.
11. Kapitsa, P. L., *Dokl. Akad. Nauk. SSSR, 101,* 245 (1955); *Phys. Blätter, 14,* 11 (1958); *Ball lightning,* Consultants Bureau, New York, 1961, pp.11-16.
12. See Singer (1971), pp.133-145; Singer, S. "Ball Lightning", in Golde (1977) pp.420-423; Barry (1980) pp.200-201.
13. Turman, B. N.: "Detection of Lightning Superbolts", *J. Geophys. Res., 82,* 2566-2568 (1977).
14. See Singer (1971), pp.98-111; Barry (1980), Ch.7.
15. See Barry (1980), p.41; Corliss, W. R. (1982) *Lightning, Auroras, Nocturnal Lights, and Related Luminous Phenomena,* pp.110-120. Pub'. by Sourcebook Project, P.O. Box 107, Glen Arm, MD 21057, U.S.A.

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This prefabricated chicken-breeding unit for 12,000 birds at a farm near Southwell, Nottinghamshire, was torn apart by a T3 tornado in the jumbo outbreak of 23rd November 1981 *(Newark Advertiser)*. The debris extends for over a kilometre into the distance.

Close-up photograph, by Mr. Les Irving, of the base of a waterspout crossing sands at Barmouth, Wales, on 22nd September 1984.



*Case Studies of Recent Tornadic Phenomena*

# A WATERSPOUT OBSERVED NEAR BARMOUTH IN SEPTEMBER 1984

By JOHN P. SMITH
*School of Applied Sciences, Wolverhampton Polytechnic*
and
ROBIN HARPER
*Bryn Mynach Road, Barmouth*

A tornadic waterspout formed beneath a strongly developed cumulus cloud within a line-squall some 2-3km offshore from the town of Barmouth in west Wales, on the evening of Saturday 22nd September 1984. Although few direct instrumental observations of the prevailing meteorological conditions could be obtained, a wealth of visual observations, still photography, and a video film were made by several people. The photograph in Fig.1 represents a typical view. By instituting a programme of systematic interviews and collation of the lines of sight and timings we have been able to deduce the direction of travel of the tornadic vortex and parent cloud (Smith and Harper, 1985). From various sources the speed of movement of the tuba was estimated, and from the damage done estimates of the strength of the system using the TORRO scale were made.

Fig.1: The Barmouth waterspout, photographed from Llanaber by David Bird, while still gaining in intensity and not long after its formation.

The most notable features of the waterspout were:

1. After initiation, the waterspout moved over the sea towards the town with the same speed and direction as the parent cloud and prevailing windfield.
2. On approaching the shore and the high ground behind, a marked inflection in the path occurred, and the vortex then began to pass across the harbour and into the mouth of the Mawddach estuary.
3. The surface vortex then progressed along the northern side of the estuary

on a track diverging from that of the parent cloud which continued to the E.S.E. with the airstream aloft. This resulted in the development of an 'S' shaped tuba.

4. The surface vortex continued along the estuary with no visible connection aloft and moved with greater speed as it progressed up the estuary. It finally dissipated at a point where the estuary is rather constricted

5. Overall, the surface track of the waterspout was 9-9.5km long with a duration of about 15 minutes. The average speed of translation of the system was therefore 36-38 km/h with a range from about 30-55 km/h. The direction of rotation of the vortex was cyclonic. Generally, damage was light with a number of small open boats swamped, garden furniture overturned, and a flagpole snapped. The system was estimated to be T2 on the TORRO scale when at its maximum development.

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## TORNADO AT SMARDEN, KENT, 5 SEPTEMBER 1980

By CHRISTOPHER R. CHATFIELD
*32 The Cockpit, Marden, Kent*

An illustrated account is given of the damage caused by a T2-3 tornado which struck Smarden at 1050 GMT on 5th September 1980 during a severe thunderstorm. The investigation and eye-witness interviews were carried out the next day. Unusually, it turned out that the farm which was the first hit, Vesper Hawk Farm, had suffered during another tornado 14 years earlier, on 2nd January 1966.

The tornado formed from a thunderstorm just before 1050 GMT and touched down about ¼km south of the village. It moved in a direct line N.N.E. towards the east end of Smarden, but lifted off the ground before reaching the village. The funnel did not dissipate, but made a rather sharp turn towards the E.N.E. before touching down again and producing its strongest outburst of energy. After travelling ¼km in another direct line, the tornado lifted suddenly, and no further ground contact is known, although rotation was maintained for a considerable distance; the funnel was last seen near Canterbury, 25km to the north-east 1½ hours later. I spoke to several people at Smarden who had seen the tornado – clouds gathered together and a vortex extended downwards, forming a funnel like a pillar of smoke. The most destructive part of the tornado's track was obvious by wounds on trees where large branches had been torn off, and by heaps of branches strewn in fields. There were two damage tracks, each ¼km long, separated by a 'skip-distance' of ½km. In the first track, the main damage was on the right side, where translational velocity augmented rotational velocity, but after the 'skip-distance', main damage was on the left side. The change in direction while the tornado was airborne seems rather odd. The funnel was still active during this period, as shown by light treetop damage and by the fact that two large apple trees, otherwise undamaged, lost all their fruit, presumably as they were violently shaken by the windflow into the vortex. The tornado damage track was about 40m wide at the ground.



## A TORNADO IN GERMANY, SEPTEMBER 1984, AND TORNADOES IN HERTFORDSHIRE, NOVEMBER 1984

By WILLIAM G. COLLINS
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While in holiday in Germany, at Remagen on Rhine, I had my first experience of a tornado, at about 4.00 a.m. on 7th September, when my sleep was disturbed by an ever-increasing roar – firstly, like an advancing express train and, swiftly, like a jet plane crashing on or near my hotel. The tornado was probably associated with an occluded front. The hotel building was of sound structure, and did not appear to have been damaged.

Two months later a tornado hit a residential estate in my home town of Hitchin and, a few minutes later, a newly-occupied housing estate at Aston End on the eastern outskirts of Stevenage. The date was 23rd November and the time about 2030 GMT. I likened the scene in Aston End, from my experience in war-time following air-raids, to one of a bombing incident, especially that of a flying bomb. Roofs and tiles were damaged, fences were down to ground level, and 4-ft high newly-built walls had been blown over, in numerous cases to 1-brick level. The damage at Hitchin was less severe, partly because the housing property seemed to be of a higher standard, but many roof tiles had nevertheless been ripped off by the whirling wind.

## A VIDEO TAPE PRESENTATION OF TORNADOES IN BRITAIN

By JOHN M. HEIGHES
*60 College Road, Sandhurst, Berkshire*

Among the video tapes presented are sequences showing the tornado funnels of 24th June 1979 at King's Langley (Hertfordshire), 23rd June 1982 at Potter Heigham (Norfolk), and 2nd August 1984 at Gotham (Nottinghamshire) (accounts of these tornadoes were given in *J. Meteorology, 6*, 233-240; *7*, 344; and *10*, 124-127, respectively). The Gotham tape, and some others, show various types of tornado damage to buildings.

Vortices associated with the *Torrey Canyon* fire disaster and the Surtsey volcanic eruptions are also being shown.

## TORNADO-WATERSPOUT RISK AT THE SEVERN BRIDGE

By G. T. MEADEN

On 1st March 1981 at 1615 GMT a tornadic waterspout passed transversely through the great Severn road bridge near its western end adjoining Beachley, Gloucestershire. Judging from the several available damage indicators in the vicinity of the bridge, a conservative tornadic intensity of T2 was assigned, where T2 corresponds to a wind-speed range of 33-41 m/s or 73-92 mph. At the bridge the wind-speed was most probably at the top of this range. In incidents at Beachley a caravan was destroyed and a large part of the roof of a house was thrown against the bridge supports. Full details are given in *J. Meteorology, 8*, 37-45. Along the same track 22km to the N.N.E. the tornado later brought down trees and caused other T2 damage at Ayleford, near Soudley, Gloucestershire. For much of its path the tornado followed the Severn as a tornadic waterspout; its intensity at maximum development was considered to be T3, 42-51 m/s (93-114 mph). (Figs.1-4).

Two years afterwards, following the discovery of structural weaknesses caused by considerable corrosion, a firm of consulting engineers (Mott, Hay and Anderson) issued a report declaring that the bridge "may not survive a wind speed of 100 mph" and recommended stopping the traffic flow when winds of 70 mph are forecast. This disturbing statement was almost as amazing as that of Messrs. Freeman, Fox and Partners, designers of the suspension bridge who admitted that the bridge (completed in 1966) was only planned for a maximum speed of 100 mph (45 m/s) at carriageway level.

From this it is obvious that the bridge designers made use of the official maximum 3-second gust-speed estimates for the area (British Standards Institute Code of Practice CP3) which are based upon conventional wind speed data obtained from official recording stations over many years. In fact, the figure of 45 m/s at carriageway height corresponds to a 50-year return period, suggesting a very optimistic level of risk. Moreover, and to our continued dismay in other contexts, the officially-derived gust estimates totally ignore tornadoes and waterspouts. Yet, as TORRO has shown repeatedly, Britain suffers in each decade hundreds of known damaging tornadoes, a sizeable fraction of which bear winds strong enough to put the wind-design basis of the bridge to the test, to say nothing of a corrosion-weakened one.

It is therefore of interest to do a calculation to see what the chances are of a tornado greater than T2 (42+ m/s, 93+ mph) hitting the bridge. For this purpose we simplify by noting that on the map the Severn Bridge is a linear feature, oriented W.N.W.-E.S.E., with a critical length between suspension cable anchorages approaching 2km. Next, the construction of a tornado wind rose based on British south-coast and west-coast tornadic incidents reveals the dominance of path directions from between S. and N.W. (52 analysed cases from 1960-1984: S. 3, S.S.W. 5, S.W. 14, W.S.W. 8, W. 9, W.N.W. 6, N.W. 5, N.N.W. 1, and N 1). Hence it is practicable to consider actual tornado data for well-populated sections of fairly straight south-facing coastlines oriented approximately the same as the bridge. With these limitations the best coastlines for which reasonably complete statistics are available (1960-1984) are (1) the 20-km stretch from Poole through Bournemouth and Boscombe to Christchurch (6 events, all off the sea), and (2) the 40-km coast from Angmering, Worthing, Shoreham and Southwick to Hove, Brighton, Saltdean and Newhaven (12 events off the sea, plus one from the N.W.).

This gives a combined result of 18 events crossing a 60km line in 25 years, which is equivalent to a tornado return period of 40 years for a 2km section of coastline. The result is the same for either section of coast taken separately, and may be much the same for the Severn Bridge area which is likely to have a similar tornado climatology. British tornadoes are dispersed across a range from T0 to T8. The worst south-coast events of the last 200 years were at Portsmouth in 1810



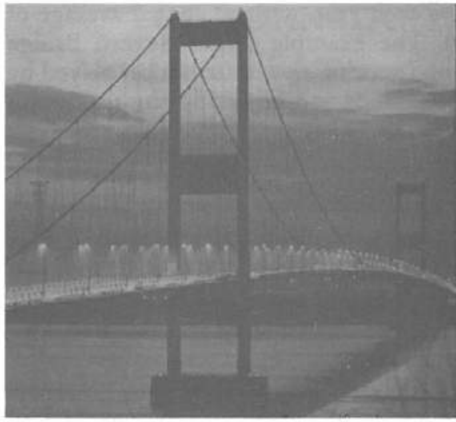

Fig.1: The Severn Bridge. Faults revealed by the 1983 survey: (1) Many of the nearly vertical cable hangers are severely corroded at their base joints, (2) the main cable saddle-casings are bursting on the tower tops, being overstressed by high traffic and wind loads, (3) the cable splay-saddles are overloaded, (4) the restraining arms of the rocker system, beneath the roadway at the towers, are worn and weak, and (5) there are cracked welds and overloaded webs in the steel box-girders of the main road span.

Fig.2: The tornadic waterspout of 1st March 1981 striking Beachley and the Severn Bridge, as photographed from Chepstow at a distance of almost 4km.

(probably T8) and Cowes in 1876 (probably T6); the devastating T7 South Wales tornado of 1913 occurred only 40km west of the bridge (cf Mike Rowe's paper). Dispersion analyses show that 40% of tornadoes are T3 or more, 15% T4 or more, and so on. This leads to return periods for tornadic mean wind speeds of 37, 46½ and 56½ m/s (83, 104, and 126 mph) of 52 years, 100 years and 270 years respectively. To evaluate the overall risk these figures require to be *combined* with the conventional gust estimates, and therefore reduce the previously-derived return periods considerably. For example., the return period for a 45 m/s (100 mph) gust falls to only 33 years.

*Concluding Remarks.* A realistic, yet necessarily provisional, attempt has been made to determine the risk probabilities for tornadic winds at the Severn suspension bridge. An overall tornadic return period of about 40 years is indicated, and return periods for different wind-speeds are developed as well. Whether or not the resulting figures represent acceptable risk levels for the survival of something as valuable as a major motorway suspension bridge is a matter of opinion, but it does seem that a design based on a maximum gust of 45 m/s, with an adjusted return period of about 33 years, hardly seems adequate for a new bridge – still less for one with severe corrosion at cable hangers, saddles, etc. Already, the anemometer on the east side has recorded wind speeds of 38 m/s (85 mph) and 37 m/s (82 mph) (in 1976 and 1974), and one T2 tornado (at say, 41 m/s, 92 mph) has passed through the west side (while others have been sighted in the region). This only goes to emphasise that expert tornado-risk opinion should be sought whenever designs of wind-sensitive structures are contemplated. Since

1971 Britain has averaged 18 tornado days each year, with an annual average of 45 incidents (see Derek Elsom's paper). The example of the Severn Bridge testifies to the dangers that can result from ignoring the contribution played by tornadoes in lowering design gust return periods and in raising the maximum gust-speeds likely within stated time intervals.

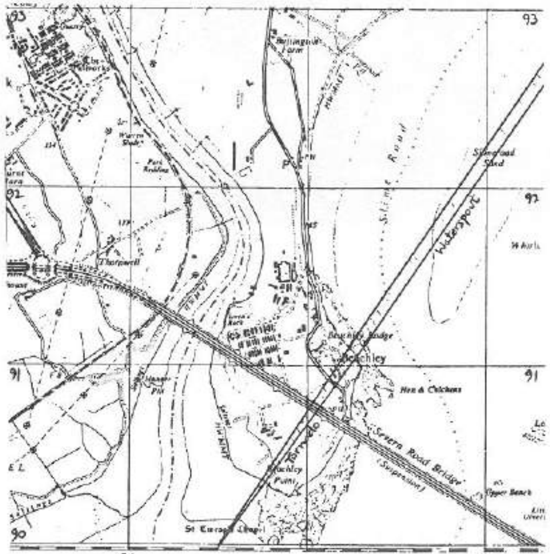


Fig.3: Map of the Beachley peninsula, Gloucestershire, showing the Severn road bridge and the path of the tornado-waterspout. The scale is indicated by the 1-kilometre squares of the national grid.

Fig.4: A caravan, 200m N.E. of the Severn Bridge, wrecked by the tornado which cut through the bridge on 1st March 1981. The missing side of the caravan was carried 400m into the Severn beyond.



# THE TORNADO THREAT IN EUROPE

## A statement by Terence Meaden and Derek Elsom on behalf of TORRO

Papers presented at this First Conference on Tornadoes, Waterspouts, Wind-Devils and Severe Storm Phenomena have demonstrated how tornadoes pose a serious threat to life and property in Britain, a threat that has for too long been totally overlooked by Civil Engineers, Aviation, and Meteorological Authorities.

It is only through much good fortune that considerable injury and loss of life have not happened in this country in recent years. Recent examples where fortuitous circumstances have prevented a tornado disaster include the force T5 tornadoes which devastated schools at Holyhead (23rd November 1981) and Llandissilio (12th December 1978) without injury to anyone. Further, the tornadic waterspout which passed through the Severn Bridge on 1st March 1981 offers a warning as to what destruction and loss of life could have occurred if the tornado had been of greater severity than force T2.

The destructive potential of tornadoes seems to have been completely ignored in structural design in this country and in the rest of Europe. For example, building design which employs the once in 50-years return-period gust-speeds implies extreme wind-speed values in England and Wales ranging from 38 m/sec at inland locations, notably south-east England, to 48 m/sec on exposed western coasts. Consequently, tornadoes of TORRO force T3, characterised by wind speeds of 42-51 m/sec, exceed the once in 50-years gust-speeds used in most structural designs in south-east England while T4 tornadoes (52-61 m/sec) exceed design speeds throughout England and Wales. An analysis of the intensity of all known British tornadoes revealed that 40 per cent of all tornadoes were of force T3 or more and that 15 per cent were of T4 or higher.

It is because many of the most severe tornadoes have had paths through rural

Fig.1: Buildings demolished at South Kelsey, Lincolnshire, by the T7 tornado of 25th October 1937. The joiners shop in the distance was rased almost to the ground.

areas rather than through large towns or cities that incidents of disaster magnitude have not occurred recently in Britain. Fig.1 shows some of the destruction wrought by the T7 tornado of 25th October 1937 at South Kelsey in Lincolnshire (see also Fig.1 of Mike Rowe's paper on p.214). Although this tornado had a path length of perhaps as much as 40km, all but two kilometres occurred in open countryside. Despite the demolished buildings there was not a single injury.

Contrast this with the T9 tornado of 24th June 1967, which traversed eight communes on a path length of 23km in the northern French department of Pas-de-Calais. Ecourt and Palleul were among the villages worst affected. There were six deaths, 30 injuries, and 300 houses damaged of which 100 were quite demolished. Or consider the devastating T8 tornado of 20th September 1982 in which 80% of the Belgian village of Léglise was very severely damaged (Fig.2).

Fig.2: Devastation at Léglise, Belgium, on 20th September 1982 caused by a T8 tornado bearing winds of 100 m/s or more.

What scale of tragedy might result if such a tornado should strike a British town, city, or series of villages? What loss of life may result if the structures included a school or a hospital? What catastrophe would result if the structures included a chemical works or nuclear power station? Why are warnings not issued when severe tornadoes are about, with at least the object of limiting injuries and loss of life?

Not only can devastation and injury be caused by the tremendously high wind-forces of tornadoes, but damage may be produced by objects being lifted and flung with considerable force. Small missiles include fragments of glass, slates, roof tiles, splinters of asbestos, roofing, and planks; large missiles include



Fig.3: An automobile hurled against a tree by the Léglise tornado on 20th September 1982.

automobiles (Fig.3) and caravans (Fig.4). Mobile homes and caravans, improperly anchored to the ground, are frequently lifted, tumbled, inverted, or smashed to pieces, to the great danger and distress of the owners.

Tornadoes have the potential for disaster not only at the ground but in the air too. On 6th October 1981 near Rotterdam in Holland 19 deaths resulted when an airliner was destroyed by a tornado over Moerdijk (W. J. Roach and J. Findlater, *Met. Mag., 112,* 29–49, 1983). In Britain one may cite the aircrash disaster of 23rd

Fig.4: Typical destruction caused by a tornado traversing a caravan park. This occurred at Tramore in Ireland on 12th October 1982.

August 1944 at Freckleton in Lancashire which resulted in 59 fatalities. This appalling event happened because the aircraft took off into a thunderstorm, and flew almost immediately into a powerful tornado near Longton, a few kilometres north-east of Southport.

STATEMENT

This conference therefore closes with a statement from TORRO intended for national and European agencies concerned with weather and public safety:

*It is formally urged that responsible authorities should*

(1) recognise that tornadoes are a significant weather hazard to which Britain and other European countries are subjected,

(2) assess tornado-risk probabilities for all European countries (as for the states of the U.S.A.),

(3) re-examine building safety standards in the light of tornadic winds especially with regard to major structures such as nuclear power stations, factories manufacturing toxic chemicals, oil refineries, suspension bridges, and many other key structures, and

(4) include tornado forecasting as part of national meteorological services, and issue tornado warnings on occasions of possible severe tornadoes (as is done in the U.S.A.).

FUTURE WORK AND ROLE OF TORRO

The future work and role of TORRO is seen as providing the basic tornado data, advice, research expertise, and consultation services required in these matters, at least in the early stages, and especially for the United Kingdom. Research into the potential threat posed by tornadoes throughout Europe merits support by government, EEC and WMO research grants. The right kind of research has been initiated by the Tornado and Storm Research Organisation, but it is less than satisfactory that research on such a serious weather hazard as tornadoes has had to await, and so far rely upon, the resources and efforts of a privately-funded body.

As this conference has shown, TORRO's expertise encompasses not only the tornado hazard but damaging hailstorms, thunderstorms, and lightning as well. TORRO offers advisory services in respect of a wide range of local weather hazards. TORRO's data collection and research programme, with its frequent publication of papers, will continue to be pursued in all aspects of severe-storm phenomena. It is anticipated that this conference is only the first of a succession of biennial conferences which document the progress and publicise the findings of TORRO.

*Acknowledgements:* Lastly, thanks need to be given to the conference organisers, the speakers, the Chairman, Michael Hunt, and the many who have worked behind the scenes preparing the conference exhibition including Heather Jones and Anna Kilmartin from Oxford Polytechnic.





Destruction of glasshouses in Cambridgeshire by a severe tornado on 26th June 1973. Warnings of an approaching tornado-force winds would be much appreciated by market-gardeners who work in glasshouses!

## WHIRLWIND DESIGNS

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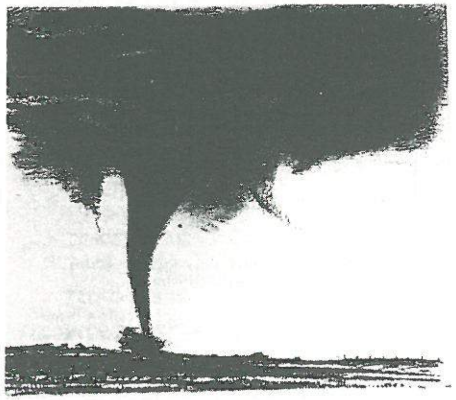

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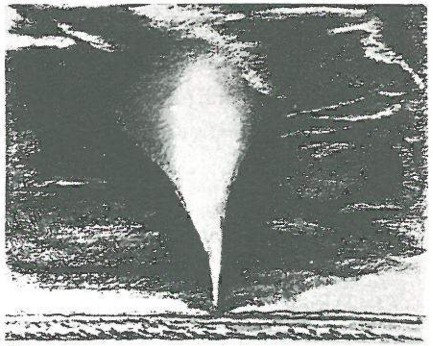

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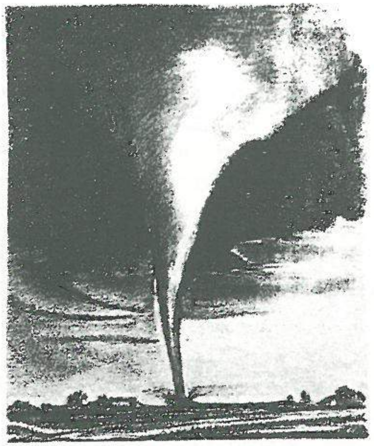

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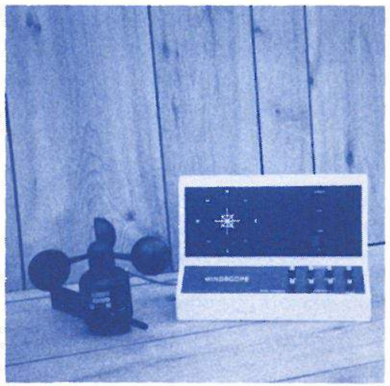

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