The
JOURNAL of METEOROLOGY

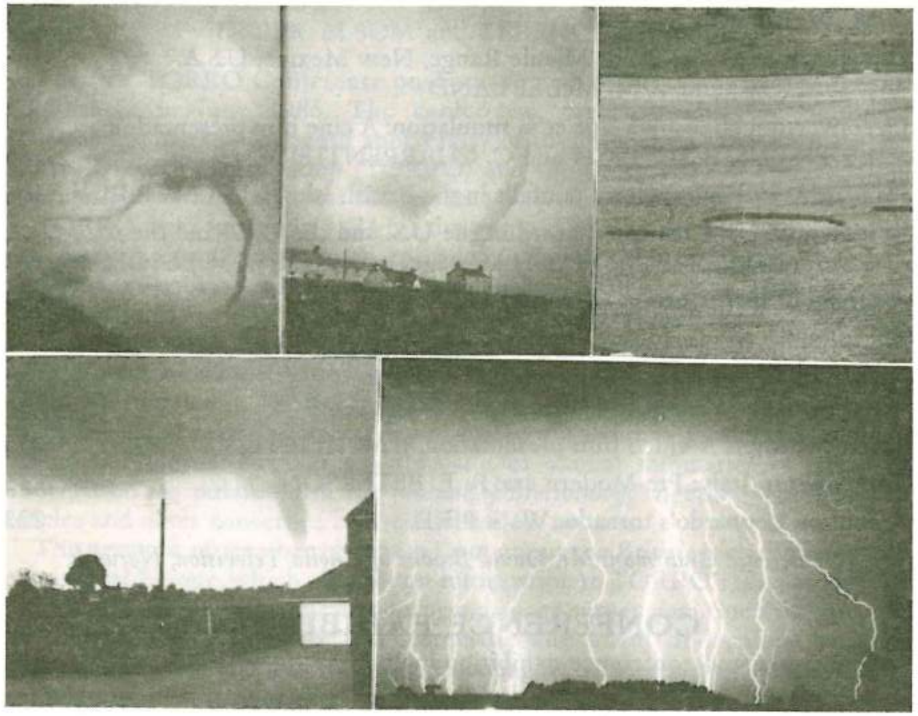
TORNADOES AND STORMS, 2

Proceedings of the Second TORRO Conference on Tornadoes and Storms

OXFORD POLYTECHNIC
4th JUNE 1988

Volume 13, number 129 **May/June 1988**

Proceedings of the Second TORRO Conference on TORNADOES AND STORMS



EDITED BY:
DR. GEORGE TERENCE MEADEN
TORRO, 54 Frome Road, Bradford-on-Avon, Wiltshire, U.K.
and
DR. DEREK M. ELSOM
TORRO, Geography Unit, Oxford Polytechnic, Oxford, U.K.
(telephone: 0865 819761 or 64777)

CONFERENCE AND EXHIBITION
HELD AT THE OXFORD POLYTECHNIC, OXFORD
4th JUNE 1988

Sponsored by the Tornado and Storm Research Organisation, TORRO.
Published by the Artetech Publishing Company, 54 Frome Road, Bradford-on-Avon, Wiltshire, England. © ISBN 0-9510590-1-7

CONFERENCE PROCEEDINGS

CONTENTS PAGE

Conference Chairman: Mr. David Brooks of Anglia Television, Norwich.

CONFERENCE EXHIBITION

The associated conference exhibition includes:

★ a display of TORRO's extensive photographic collection of British tornadoes, waterspouts, wind-devils, lightning and large hailstones as well as the damage caused by these weather phenomena;

★ a display of original drawings and paintings of tornadoes by Chris Chatfield;

★ a display of slide sets, videos and other educational materials concerned with weather studies;

★ a demonstration of meteorological instrumentation by Weather-Data;

★ a demonstration of microcomputer disk-based packages of weather radar and satellite images by Andrew Eccleston from The Computer Department, Malvern, Worcestershire;

★ a display of meteorology and climatology books organised by Blackwells Bookshop.

Frontispiece: Top left and centre, tornado funnel clouds at Walls, Shetland, 3rd July 1982 (Mrs. D. I. McElvogue); top right, triple spiral circles in ripe wheat in Hampshire, August 1981; Bottom left, tornado funnel cloud at Fleet, Lincolnshire, 9th June 1987 (B. D. Cheeseman); bottom right, lightning at Marden, Kent, 21st August 1987 (Leslie Chatfield).

SECOND TORRO CONFERENCE ON TORNADOES AND STORMS

FOREWORD

By DEREK ELSOM and TERENCE MEADEN

The first TORRO Conference on Tornadoes and Storms was held at Oxford Polytechnic in June 1985. The conference, together with the published proceedings, marked the tenth anniversary of the founding of the Tornado and Storm Research Organisation (TORRO) and the 100th issue of the *Journal of Meteorology* in which many of the research activities of TORRO are published.

TORRO was founded in 1974 for the purpose of systematising the collection and analysis of information on tornadoes, waterspouts, and other forms of whirlwinds occurring in Britain and the rest of Europe. Since then, TORRO's foci have expanded to include damaging hailstorms, thunderstorms and lightning damage (in 1981 the TORRO thunderstorm division, directed by Keith Mortimore, took over responsibility for the Thunderstorm Census Organisation, or T.C.O. founded in 1924), remarkable falls, point deluges, ball lightning, and weather-related deaths as well as day-to-day world weather disasters (collated by Albert J. Thomas). Regular monthly and/or annual summaries of collected information are published in the *Journal of Meteorology* together with research articles and notes concerned with these subject matters.

The network of weather observers throughout the British Isles and in nearby continental Europe, which contributes information to TORRO's files, produces a wealth of local meteorological and storm damage survey data. Such information not only provides the only real systematic assessment of localised weather phenomena (as for example, the paper on damaging hailstorms by Jonathan Webb, and the paper on ball lightning by Mark Stenhoff) but it provides the local detail needed for the study of larger weather systems such as the exceptional 15th-16th October 1987 storm in southern Britain (paper by Michael Rowe). The information also provides the basis for developing our understanding of the meteorological conditions which produce localised weather phenomena. For example, not only has this led to an increased understanding of the conditions which produce tornadoes but it has led to the discovery of new forms of whirlwinds such as descending vortices which create the 'mysterious circles' found in corn fields in southern England (paper by Terence Meaden).

Whereas the First TORRO Conference focussed attention on the findings and implications of research being undertaken in Britain, the Second TORRO Conference expands its coverage to include learning about research in other countries. Professors John Snow and Thomas McClelland (Purdue University, USA) discuss their investigations into dust-devil formation in New Mexico. Over 3,100 dust devils, together with meteorological observations of lapse rate, wind speed and cloud cover, were studied in order to understand the conditions which produce dust devils. Professor Jean Dessens (Centre de Recherches Atmosphériques, Lannemezan, France) presents the results of his Météotron experiments. The Météotron is a system which provides a heat output of up to 1,000 MW and is aimed at duplicating large fires in order to simulate atmospheric convection and the associated formation of cumulus, rainfall and even tornado vortices.

The First TORRO Conference concluded with a call for action concerning recognition of the seriousness of the tornado threat in Europe. While it is clear that Europe suffers fewer of the intense 'killer tornadoes' to which the United States is subjected, parts of Europe, especially Britain, experience a relatively high frequency per unit area of damaging tornadoes. Collectively, such tornadoes constitute a significant weather hazard. Further, it only takes one serious tornado incident to produce a disaster, whether this is due to an exceptionally severe tornado or simply, a 'moderate' tornado striking a vulnerable structure in which many people are present. That a European tornado disaster can occur was illustrated on 9th June 1984 in the Soviet Union, centred on the regions of Ivanovo, Gorki, Kostroma and Yaroslave, when a series of tornadoes killed 400 people. The number of deaths even exceeded the worst tornado outbreak of recent years in the United States, namely on 3rd-4th April 1974 when 315 people were killed. The experience of the Soviet tornado highlights the potential for a tornado disaster in other countries of Europe. Even if such an event is rare, the tornado hazard in many countries of Europe is sufficient for

(a) safety standards for major structures such as nuclear power stations and suspension bridges to be re-examined and,

(b) for tornado warnings to be issued in the case of large tornado outbreaks or occasions of exceptional tornadoes.

TORRO contributed to the first recommendation in 1985 by providing a report, prepared by Terence Meaden, to the U.K. Nuclear Installations Inspectorate concerned with national and regional tornado-risk potential in the United Kingdom. Similar assessments are needed for other European countries.

Elaboration on the second recommendation is given at the present conference (paper by Derek Elsom). Although forecasting tornadoes in Britain may be difficult, it is argued that the issuing of severe-weather FLASH messages for tornadoes, so as to provide a few hours warning to the public and emergency organisations, should be given serious consideration. Whereas such warnings may be necessary only once or twice a year, in connection with large tornado outbreaks or for very severe tornadoes, they are needed so as to alert the public of the 'occurrence of severe weather which may cause considerable inconvenience to a large number of people and/or present a danger to life' (the Meteorological Office condition for issuing a FLASH message). TORRO has a role to play in such warnings. First, rapid confirmation that an area has been struck by a tornado or tornadoes is needed before a tornado FLASH message for other areas can be issued – this requires reliable local weather observers. Second, the public need to have a greater awareness and understanding of the nature of the British tornado hazard – TORRO can contribute to this public education.

The First and Second TORRO Conferences, together with the frequent summaries and research reports in the *Journal of Meteorology* (and in other journals and magazines), indicate the successful progress being made by TORRO in a wide range of spheres. The Third Conference on Tornadoes and Storms, planned for two or three years time at Oxford Polytechnic, intends to continue the documentation of that progress.

Finally, the Second TORRO Conference owes its success not only to the speakers but also to the Chairman, David Brooks of Anglia Television, Norwich, to whom our thanks are extended. Our appreciation of the video sequences of severe local weather provided by John Heighes is acknowledged. In addition, staff at Oxford Polytechnic are thanked, especially Heather Jones and Anna Kilmartin, for their help in arranging the conference and the associated exhibition.

THE STORM OF 16th OCTOBER 1987 AND A BRIEF COMPARISON WITH THREE OTHER HISTORIC GALES IN SOUTHERN ENGLAND (1362, 1662, 1703)

By MICHAEL ROWE
TORRO, 21 Bankside, Lymington, Hampshire

Abstract: The storm of 16th October 1987 was one of the most destructive gales on record in south-east England. However, the damage appears to have been neither as widespread nor as severe as in the gales of 1362, 1662 and 1703, although in Kent and Sussex it may have been comparable with the storm of 1703, which was in general the most severe of the four. Major factors in the development of the 1987 storm were an exceptional thermal gradient in the upper atmosphere over the Atlantic and the existence of a sharp upper trough to the west of Britain.

INTRODUCTION

The severe gale which swept across south-east England and East Anglia during the early hours of Friday, 16th October, 1987, causing an immense amount of damage, has been widely described as possibly the most devastating gale in southern England since the famous storm of 1703. This study describes the development of the depression which caused the damage, and compares the gale with the storm of 1703 and with two others, in 1362 and 1662, which were among the most severe on record in southern England.

SYNOPTIC DEVELOPMENT

After a quiet start October 1987 had turned increasingly wet and cyclonic over most of Britain. For some days prior to the storm a depression had been centred to the west of Ireland, with a series of waves forming over the Atlantic at about latitude 42°N. At 0600 GMT on 14th October there was a wave at about 43°N, 48°W, central pressure about 998mbar, with another wave just to the east of it, while to the south-west ex-hurricane Floyd was off the eastern United States. At 0600 on 15th two waves, presumably though not necessarily the same ones, were at 42°N, 19°W (984mbar) and 47°N, 8°W (976mbar), still with only one and two closed isobars respectively (*Berliner Wetterkarte,* 14th and 15th October). Either the waves then coalesced, or more probably one died out; at any rate by 1200 on 15th there was a single low which was deepening very rapidly as it moved north-east across the western part of the Bay of Biscay towards southern England. At 1200 it was north of La Coruña, N.W. Spain, 970mbar (Fig.1); by 1800 it was south-west of Brittany, 964mbar. The low crossed south-west England and the

Midlands, and at 0600 on 16th was off N.E. England, 960mbar, having filled slightly. It then deepened again as it moved north, and at 1800 was north-east of the Shetlands. After this it moved N.N.E. across the Norwegian Sea and began to fill *(Berliner Wetterkarte: L.W.C. Daily Weather Summary)*. It should be noted that this account has been built up from charts published at the time, some of which have since been amended on receipt of further data (on Fig.1 the low at midnight should be off north Brittany, 952mbar), and that the early stages of the low are still uncertain.

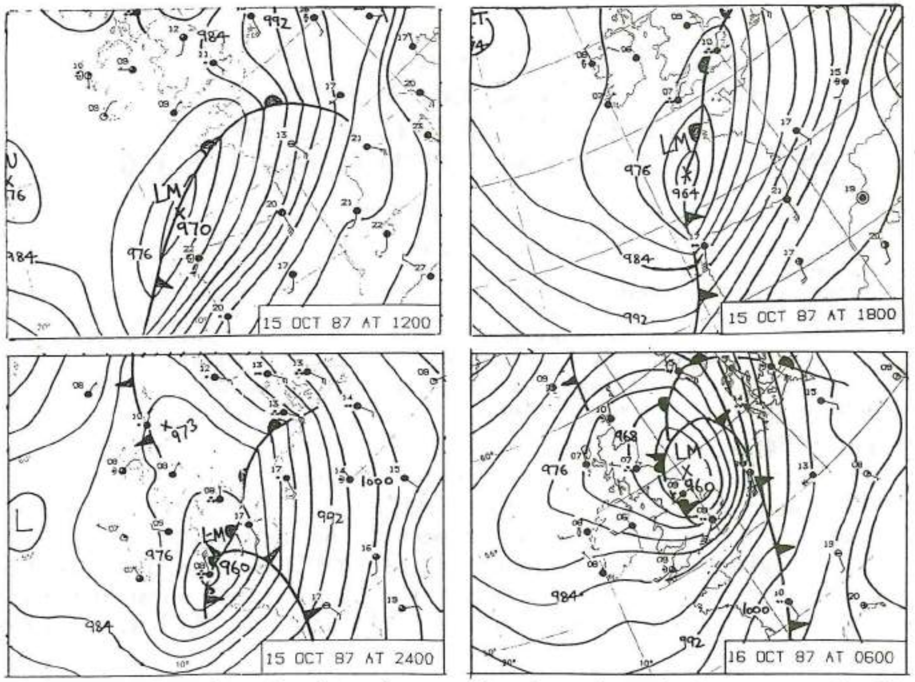


Fig.1: Synoptic charts for 15th-16th October 1987 (from the *Daily Weather Summary*, reproduced by permission of the London Weather Centre).

The explosive deepening of the low was partly due to an exceptionally large temperature gradient over the Atlantic. On 13th October unusually warm air (–4°C) was to be found at 500mbar at about 32°N, 63°W. This spread E.N.E., and at 0001 on 15th a considerable area west of the Azores had 500mbar temperatures of –3°C. This is the highest temperature recorded during 1987 in that area and at that level. At the same time temperatures at 500mbar to the west of Britain were unusually low, and on both 14th and 15th were around –28°C at 50°N, 20°W. This was the lowest value at that point since 4th April 1987, and it was not reached again there until 27th December 1987. By 16th October some of the warm air had reached southern Spain (–5°C at Madrid at 500mbar), while –30°C was measured as far south as 45°N, 22°W. According to Hoskins and James (1987) the warm air had probably originated in hurricane Floyd, which was off the coast of Florida on

13th, the air spiralling into the hurricane at low levels and later being ejected at higher levels before being transported across the Atlantic by a jet stream. It was when the surface low approached the jet stream that the explosive development took place. The presence of a sharpening upper trough to the west of Britain was also a factor.

ACCURACY OF THE FORECASTS

In view of media criticism of the British forecasters on this occasion, and the suggestions that some other European countries' forecasts were more accurate, it is worth noting that the forecast surface chart for 0600 on 16th, issued by Bracknell 24 hours earlier, was extremely accurate. The centre of the low was predicted to be off S.E. Scotland, 962mbar, not far from its actual position and pressure off east Yorkshire, 960mbar. The position of the fronts was also almost precisely correct. The West German forecast chart (published in the *Berliner Wetterkarte*), on the other hand, got the location and depth of the low, the position of the fronts and the degree of occlusion very significantly wrong, placing the centre of the low over the Channel Islands, about 973mbar, at 0600 on 16th, with occlusion not yet having begun.

UNUSUAL FEATURES OF THE STORM

Apart from the high winds, two other features of great interest during the passage of the low were the extremely high temperatures in south-east England during the night, and the enormous pressure rises in southern England in the rear of the low. At Hurn (Bournemouth) and Heathrow the temperature, which had been a fairly normal 9°C at 1800 on 15th, was 17°C at midnight. Manston (Kent) and Hurstmonceux (Sussex) recorded 18°C at 0200. There are several dates towards the end of October for which the highest recorded United Kingdom *maximum* since 1875 is 18 or 19°C (Meaden and Webb, 1984). Pressure rises as the low moved away exceeded 20mbar in three hours over much of southern England (Fig.2). At Mortimer, Berkshire, Stephen Burt recorded a rise of about 25.5mbar between 0430 and 0730 (Burt, 1987). The previous record three-hour pressure rise in the British Isles this century appears to be one of 21.6mbar at Lerwick, Shetland, on 15th January 1952; the largest known three-hour fall is 23.5mbar at Valentia, S.W. Eire, on 22nd October 1961 (Burt, 1985).

DAMAGE

The storm of 16th October 1987 will, however, mainly be remembered for the enormous damage that it wrought in south-east England and East Anglia. Fig.3 shows the locations of damage sites mentioned in the national press of 17th October and *The Observer* of 22nd November. *The Observer* gave an excellent, detailed list of parks and gardens that suffered damage (Buchan and Lacey, 1987). Of the 1,200 gardens in English Heritage's 'Register of Parks and Gardens of Special Historic Interest in England' about 350 were affected by the storm. Of these, up to 100 were 'badly damaged', with a substantial number of trees uprooted; 30 or 40 were devastated. Of woodland gardens, the most severely damaged were Emmetts and Sandling Park in Kent, and Leonardslee, Sheffield Park, Nymans and Wakehurst Place in Sussex. Severe damage to parks, gardens and woodland extended from west Hampshire (where Broadlands, near Romsey, lost 700 trees) to north Norfolk. There is some evidence that the damage was less severe in East Anglia than further south: Somerleyton Hall, Suffolk, lost fewer trees than in the gale of 2nd January 1976, and Cambridge University Botanic Gardens lost fewer than in the gale of 24th March 1986. Thetford Forest, Norfolk, on the other hand, lost more than in 1976. Some estimates put the total number of trees lost in England during the storm at 15,000,000. Fruit growers lost 300,000 trees, with another 500,000 badly damaged.

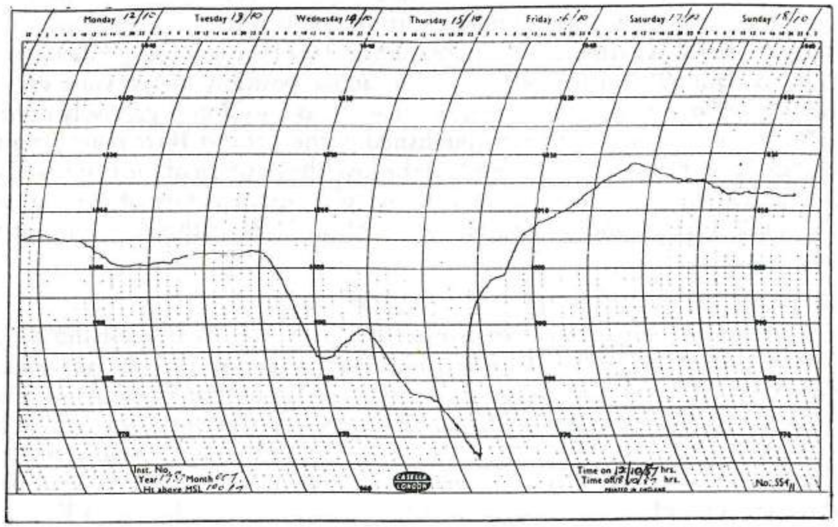


Fig.2: Barograph record for Tolworth, Surbiton, Surrey, 12th-18th October 1987 (Peter N. Ashdown).

Property damage was again worst in the extreme south-eastern counties. In London, Camden alone had 400 houses damaged. The London Fire Brigade, which normally receives 350 calls a day, received 6,000, almost twice the previous record for a single day. Most of the 18 people who died in the storm were killed by falling trees or by the collapse of part of a building; half the deaths were in Kent and Sussex. Chichester Cathedral was damaged, as were both the cathedrals at Portsmouth, the Anglican one by stones from the beach. Over 600 schools were shut in Kent on 16th October, and all 280 in East Sussex (over 50 being severely damaged); most in West Sussex; over one third in Inner London; one third on the Isle of Wight (half of which were damaged); all 29 in Jersey – at least 3,000 in the whole country.

The gale also caused havoc on the coasts. On the Isle of Wight, Shanklin pier collapsed; in Essex, a yacht marina at Wallasea Island was almost destroyed. A number of ships went aground or sank; two men were drowned when their ship capsized off Dover. At Topsham, on the Exe estuary in Devon, well outside the main area affected by the gale, three fishing boats sank. Mobile homes and caravans suffered enormous devastation. At Peacehaven, Sussex, over 200 caravans

were wrecked, and damage on a similar scale occurred at Hayling Island (Hampshire), Selsey (Sussex) and Clacton and Canvey Island (Essex).

Throughout the storm-damaged area, from Dorset to Norfolk, electricity supplies were disrupted for many hours. In the south-east, especially, many places remained without electricity for several days, and in some parts of east Sussex and Kent it was almost two weeks before power was restored. Repair work was greatly hampered by the number of roads blocked by fallen trees. British Telecom lost 3,000 miles (5,000 kilometres) of telephone wires, and 3,000 poles were damaged or destroyed.

There has been much discussion about how exceptional the storm of 16th October 1987 was, and it has been suggested that it was the worst in southern England since the storm of 1703, which is by far the most famous in British meteorological history. The rest of this article gives a brief account of three exceptionally severe gales that have struck the south of England, and attempts to assess the severity of the 1987 storm in relation to the earlier ones.

THE GALE OF 23rd JANUARY 1362

A description of the 1362 (15th January, Old Style; 23rd January, New Style) has been given in the *Journal of Meteorology* by the late Michael Hunt (1980), with additional primary source material provided by Dr. Meaden. The chroniclers are in general agreement that the gale blew from the south-west and occurred during the evening. Several modern writers have regarded this as probably the most severe gale on record in southern England apart from the storm of 1703. The chronicle evidence is rather too scanty to prove this point, but the damage certainly appears to have been exceptionally severe: the bell towers at Bury St. Edmunds, Norwich, London and elsewhere were destroyed. A few damage sites can be added from *The Black Prince's Register* and the *Calendar of Patent Rolls,* and further evidence could certainly be found in other administrative documents. The Black Prince (eldest son of Edward III) lost a considerable amount of timber on some of his estates. The map in Fig.3 suggests that the storm was probably worst in the southern half of England, and worse in the east than the west (although it is known to have been very violent in Dublin). At the two most northerly locations on the map, Kirkbymoorside and Cottingham, the damage, though stated to be due to wind, may not have occurred in the storm under consideration.

'WINDY TUESDAY', 28th FEBRUARY 1662

Of this storm, which occurred on 18th February by the Old Style (Julian calendar), Schove (1986) remarks: "This was in N.W. Europe the most notorious gale between 1362 and 1703". It is described in considerable detail by Defoe (1704), quoting the earlier work *Mirabilis Annus.* The damage seems to have been confined to the southern half of England (Fig.3: the map has been compiled from the information given by Defoe, except for a few locations given in the *Calendar of State Papers (Domestic)).* Buildings were very severely damaged; many barns and vast numbers of trees were blown down. Defoe and the State Papers agree that at least 3,000 trees were lost in the Forest of Dean; Brampton Bryan (Hereford and Worcester) lost over 1,300 according to Defoe. These figures suggest devastation comparable with that experienced in Sussex and Kent in the 1987 storm. At least 17 people were killed; this is a very high death toll when one considers that the

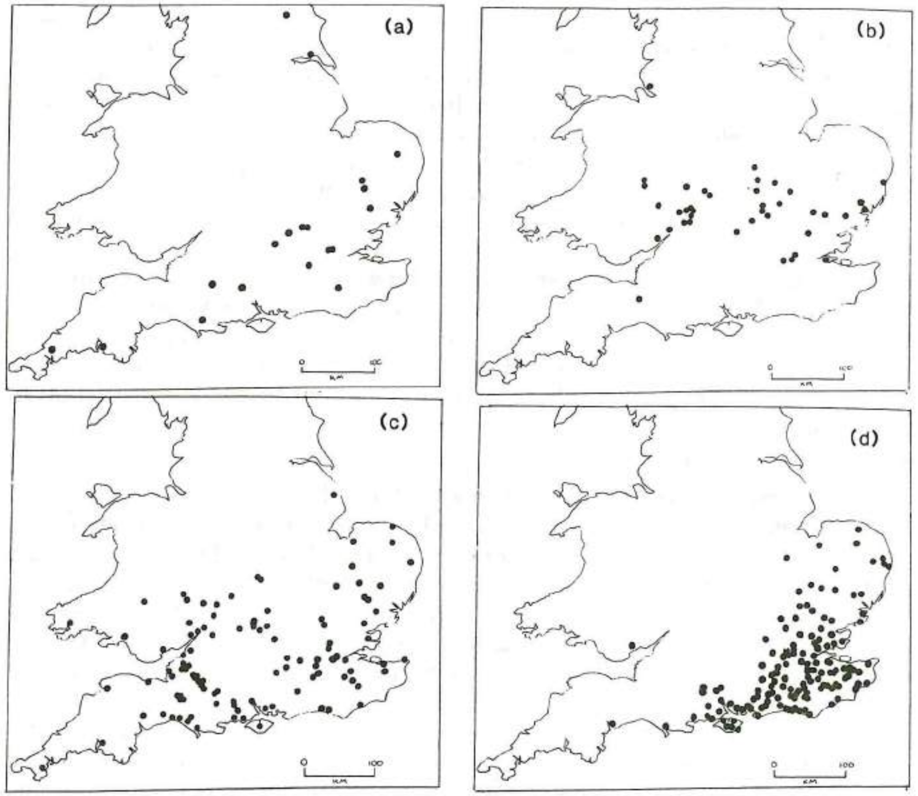


Fig.3: Known damage sites in four severe storms: (a) 23rd January 1362; (b) 28th February 1662; (c) 7th-8th December 1703; (d) 16th October 1987. The small number of sites shown on the first two maps is due to lack of data, and does not of itself indicate that the storms in question were less severe than the other two.

population of England was then only one-tenth of what it is today. There are at least two apparent references to tornadic action (if the accounts are not exaggerated): in Hereford several people were lifted into the air, one allegedly to a height of six yards; and in Hertfordshire a man was lifted over a hedge and carried a distance of one pole (five metres). There is some evidence from Fig.3 that the storm may have been less severe near the south coast.

THE GREAT STORM OF 7th-8th DECEMBER 1703

All authorities are agreed that this was the most devastating gale to strike southern England in recorded history. Although there is little doubt that this is true, the impression is partly due to the fact that a large number of detailed and often dramatic descriptions of the storm and its effects are conveniently available in one work – Daniel Defoe's *The Storm* (1704) – whereas an account of most other historic storms has to be pieced together from scattered and often brief references. It is possible, for example, that if the storm of 1362 were more fully documented it might appear to rank with that of 1703. Most writers who have mentioned the

latter have relied mainly on Defoe, but there is a large amount of independent information, mainly from ships' logs, in a valuable article by Harries (1897). Brooks (1927, 1954) produced a synoptic chart for 0400 on 8th December 1703 (27th November, Old Style), which is probably reasonably correct, although the data given by Harries suggests some amendments.

Almost everywhere south of Birmingham suffered very severe damage. Houses lost chimneys or even the whole roof; a few houses were completely destroyed. Many churches were badly damaged; in a number of cases the lead on the roof was rolled up and carried away by the wind. Huge numbers of trees were uprooted (4,000 in the New Forest; over 1,000 at Brocket Hall Park, Hertfordshire). The death toll is usually given as 8,000, but this is an educated guess by Defoe. Most of the deaths were at sea (Defoe says that about 123 people were killed on land, which is itself an astonishingly large number), and although some of the ships that Defoe describes as "not heard of" may well have got safely into some port, it is quite clear that the number of men lost at sea must have been several thousand. "Above 80" people were drowned in a storm surge along the Severn estuary.

CONCLUSION

Of the four storms studied here the gale of 16th October 1987 probably affected the smallest area and was probably the least severe, although in Sussex and Kent, and perhaps in neighbouring areas, it may have been almost comparable with the storm of 1703, which was the most severe of the four. One must bear in mind, however, that the trees were still in leaf at the time of the 1987 storm and this, together with the very wet soil, must have made them more vulnerable. The storms of 1362 and 1662 are too sparsely documented for one to be certain about their severity, though the gale of 1362 was probably the more severe of the two.

REFERENCES

BROOKS, C. E. P. (1927): An early essay in co-operative meteorology: the great storm of 1703. *Meteorological Magazine, 62,* 31-35; *ibid., 62,* 91.

BROOKS, C. E. P. (1954): *The English Climate,* 29-31. London, English Universities Press.

BUCHAN, URSULA and LACEY, STEPHEN (1987): Gone with the winds. *The Observer,* 22nd November 1987, Section 5, ii-iii.

BURT, S. D. (1985): Remarkable pressure fall at Valentia, 17th October 1984. *Weather, 40,* 48-51

BURT, S. D. (1987): The severe gale of 16th October 1987 in Berkshire and Hampshire. *J. Meteorology, 12,* 332-338.

Calendar of Patent Rolls, 1361-1364. London, H.M.S.O. (1912).

Calendar of State Papers (Domestic), 1661-1662. ed. Mary Anne Everett Green. London; Longman, Green, Longman and Roberts (1861).

DEFOE, DANIEL (1704): *The Storm: or, a Collection of the most Remarkable Casualties and Disasters which happen'd in the late dreadful Tempest, both by Sea and Land.* London.

HARRIES, HENRY (1897): The great storm of 1703. An anniversary study. *Cornhill Magazine,* New Series, *3,* 579-593.

HOSKINS, BRIAN and JAMES, IAN (1987): How Britain's bomb blew up. *The Observer,* 22nd November 1987, Section 5, i.

HUNT, MICHAEL (1980): The great storm of 15th January 1362. *J. Meteorology, 5,* 61-62, with additional material supplied by G. T. Meaden, *ibid.,* 62-63.

MEADEN, G. T. and WEBB, J. D. C. (1984): Britain's highest temperatures for every day of the year, 1st January to 31st December. *J. Meteorology, 9,* 169-176.

Register of Edward the Black Prince. London, Public Record Office (1930-1933).

SCHOVE, D. J. (1986): The weather of Pepys, 1660-1669: Part 1. *J. Meteorology, 11,* 73-88.

DUST DEVILS AT WHITE SANDS MISSILE RANGE, NEW MEXICO, U.S.A.

JOHN T. SNOW and THOMAS M. McCLELLAND
Purdue University, West Lafayette, Indiana 47907, U.S.A.

Abstract: During the period 13th May through 21st August 1986 and 3rd April through 28th May 1987, a dust devil census was conducted at the Permanent High Explosive Test Site, a facility on White Sands Missile Range, New Mexico. In a 13km x 20km area, a total of 3,136 dust devils were counted on 97 days (out of 112 observing days). The dust devils were found to be highly localised in area of occurrence (being concentrated in two relatively small regions and along cleared strips associated with roadways). However, the spatial distribution in 1987 was found to be quite different from that observed in 1986.

Collateral meteorological observations indicate that the 15-minute average lapse rate in the 0.5- to 10-meter interval must exceed ca. 0.25°C m^{-1} for there to be significant dust devil production. The occurrence of dust devils appears to have been only weakly dependent on the ambient wind speed, at least up to wind speeds of about 9m s^{-1} (only very few wind speeds greater than 9m s^{-1} occurred during the census period). Cloud cover, which modulated the incoming solar radiation, appears to have been a controlling factor, most dust devils being associated with periods of only a few tenths of cover or less over the region.

Some conjectures concerning the causes of the year-to-year variation in spatial distribution are given. These suggest that the variation is an example of inadvertent weather modification.

We begin by reviewing some of what is known about dust devils. We then briefly describe preliminary results of a dust devil census conducted in 1986 and 1987 at a site in south-central New Mexico. Included are a summary of the observed temporal and spatial distributions of these whirlwinds, and a description of the background meteorological conditions within which they formed.

Here we will generally use the term whirlwind synonomously with dust devil. But strictly speaking for the moment, a whirl of the type in which we are interested is a rotating column of buoyant air containing a concentrated vortical core. If the air flow becomes sufficiently intense to loft surface material (typically dust and sand, and small vegetative debris), the whirl becomes visible and is termed a dust devil. It is through the addition of rotation that a simple upwelling thermal is reorganised into a swirling flow. As such, the whirlwind represents a mode of buoyant convection occurring under conditions of extreme thermal instability.

Why should one study dust devils? Even when these whirlwinds occur in inhabited areas, they are generally at most a nuisance, but they can occasionally be harmful and damaging. The literature contains several accounts of buildings being damaged by dust devils. Indeed, Fujita (1973; *Weatherwise, 26,* 56-62) has noted that about one-half of all confirmed tornadoes are weaker than strong dust devils. So while the winds in a dust devil cannot be considered an especially threatening hazard, in special cases there can be sufficient risk to warrant studies to determine factors such as the maximum wind speeds that are likely to occur in these whirlwinds and the meteorological conditions in which they can be expected to form.

Further, dust devils represent one of the few mechanisms known for lofting large particles high into the atmosphere. The build-up of a dust layer at 2 to 3km by mid-afternoon over some arid regions may be due to lofting of dust by these whirlwinds. This lofting may have important consequences regarding the spread of surface contaminants in such regions.

It should be noted that dust devils have been observed on Mars. It has been speculated that because of their ability to loft large particles, these whirlwinds play a key roll in the initiation of the large storms on that planet.

Yet another reason for examining dust devils is that the presence of these whirlwinds is symptomatic of the occurrence of strong convection in the planetary boundary layer. Thus a potential collateral benefit of any investigation of dust devils is an increase in the understanding of this convective mode.

Finally, dust devils have also been hypothesised to be natural small-scale analogs to waterspouts and tornadoes, and so can be studied for the purpose of learning more about these less approachable vortices. During the census described here, visual observations of the flow in dust devils indicated strong correspondence between even small structures to be seen in these whirlwinds and those reported by Golden (1974; *J. Appl. Meteor., 13,* 676-692) in waterspouts.

Exactly how dust devils are formed remains unknown. While the whirl always appears coupled to a strong thermal plume so that it is fairly certain buoyancy drives the upflow, the source of the rotation remains obscure. Laboratory studies

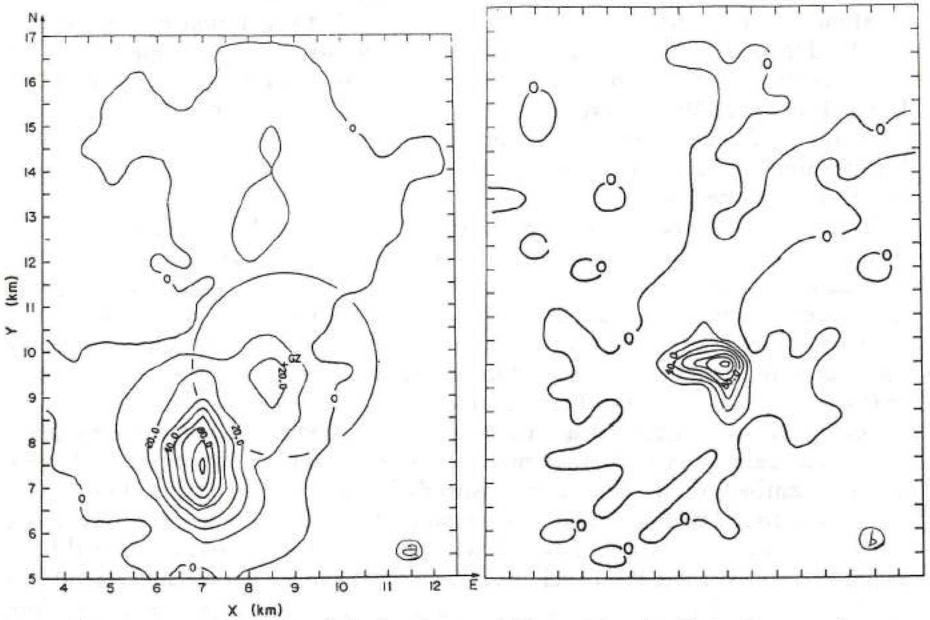


Fig.1: (a) A contoured mapping of the distribution of observed dust devils for the 1986 observing period. Contours are in units of "number of observed dust devils per 0.25km²". Note that this is only a portion of the total observational area. The circle of 2km radius shown centered on Ground Zero (GZ) encloses most of the disturbed surface. (b) As in (a) but for 1987 observing period.

indicate that concentrated whirls can form spontaneously, as part of the convective process, in a fluid with no net circulation. Observational studies suggest that eddies generated by flow around large topographic features contribute in some cases. It appears likely that the rotation can arise from several sources.

Field studies at the El Mirage, California dry lake in the 1960's and early 1970's, where it was likely that topographic effects were small, suggest that the thermal structure of the planetary boundary layer is a controlling factor. Also, over short periods of time, the dust devils showed a preferential direction of rotation. This suggests that in the highly unstable boundary layer, there are small regions of circulation of one sign (in agreement with previously mentioned laboratory studies).

The goals of the dust devil census program at White Sands Missile Range were to determine the spatial and temporal distributions of dust devils in a 260-km^2 region and to relate these to the background meteorology. The observation program was designed to collect the data necessary to establish relationships between dust devil production, local topography, and the diurnal evolution of the superadiabatic surface layer and overlying well-mixed layer.

The census was conducted in the vicinity of the Permanent High Explosive Test Site of the Defence Nuclear Agency. This test site is located in a large basin in central New Mexico. In terms of general climate and vegetative cover, this region can be classified as medium-elevation, semi-arid ranch land.

About 5 to 6km^2 of the test site has been cleared of vegetation and extensively modified through bulldozing and grading. This modified region is roughly circular and is centred on the Ground Zero of the test site (located at Lat 33°37"11'N, Long 106°28"26'W, Elevation 1504.5m MSL). A network of gravel roads converge on Ground Zero. Several other roads also criss-cross the area. All have broad shoulders and drainage ditches that are routinely graded to remove vegetation and debris.

The soil in this area is a fairly loose mixture of sand, small gravel, and loess. Its surface has a brown coloration (albedo of 0.25 to 0.3) and low thermal conductivity. Undisturbed areas do have a sparse cover of low vegetation, which is dark green in spring but changes to light brown by mid-summer. The layer of soil is typically about ten centimeters deep, so that grading operations generally expose the underlying caliche, a yellow-white chalk-like material. Caliche has an albedo of 0.4 to 0.5, and very low thermal conductivity.

Somewhat surprisingly, inspections of both the undisturbed and the modified surfaces revealed very little loose material to be present under normal conditions. The undisturbed surface generally consisted of a hard-packed crust and a covering of soil was found difficult to abrade because of the embedded small gravel; any small scar would be quickly covered with the gravel as the loose material blew away. Where exposed, the caliche was found to have a hard surface, resembling dried mud. However, the caliche is easily abraded to produce a fine powdery dust.

Between the close of the 1986 observing period and the start of the second observing period in 1987, site preparations were extensive. The size of the modified area around Ground Zero was increased, and the surface in this area was freshly graded. Also, as a result of increased vehicular traffic on Ground Zero in

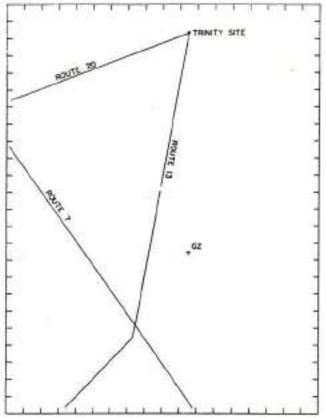


Fig.2:
A sketch map showing the road network in the vicinity of Ground Zero. The scale is the same as in Fig.1.

1987, the amount of dust on this disturbed area was appreciably increased over that present in 1986. In some places, this resulted in a surface dust blanket 2 to 3cm thick.

The dust devil census was conducted in two observing periods, the first between 13th May and 21 August 1986, the second between 3rd April and 28th May 1987. Statistics concerning the observing periods are included in Table 1. At least one observer was on-site from approximately 0700 to 1600 MST each day, usually for 5 days per week.

For the census, the designated observational area was a 13km (W-E) by 20km (N-S) tract that included the test site. The observation point for the census was on a ridge about 6km north of Ground Zero and about 100 meters higher in elevation. It was possible to survey the entire basin from this location.

Data taken for each observed dust devil included the times and locations (azimuth and range from the observation point, and grid square on the map) of first and last appearance. The observers also made an estimate of the diameter of the dust column at surface, categorizing it as *small* (diameter D less than 1m), *medium* (1m to 10m), *large* (10m to 100m), or *gigantic* (D more than 100m).

Throughout both observing periods, a 10-meter tall meteorological tower was positioned near the center of the test area. Sensors on this tower provided temperature at five levels and wind speed and direction at three levels. The sensor outputs were sampled once every minute and then logged as 15-minute averages. In addition, every half-hour the observer recorded an estimate of surface wind and regional cloud cover.

We turn to the initial results of the analysis of both the census data and the collateral meteorological data. We first provide some general results, and then describe events observed on one very active day. Due to differences in the observed spatial distributions, the data from the two observing periods are analyzed separately.

Table 1 summarizes the results of the census for the two observing periods. A total of 3,136 devils were counted in the 260km^2 region. A few highlights are given in the following paragraphs.

★ In 1986 (1987), there was an average of 35(28) devils observed per day.

TABLE 1: Summary of Observations.

	For 1986
Period of Observations:	13th May – 21st August 1986 (101 days)
Observing Days:	71
Days with one or more dust devils:	61
Number of small dust devils:	1,006
Number of medium dust devils:	1,060
Number of large dust devils:	50
Number of gigantic dust devils:	1
Total number of dust devils:	2,117
Area in which dust devils were observed:	64.5km^2 (out of 260km^2)
	For 1987
Period of Observations:	3rd April – 28th May 1987 (56 days)
Observing Days:	41
Days with one or more dust devils:	36
Number of small dust devils:	33
Number of medium dust devils:	913
Number of large dust devils:	65
Number of gigantic dust devils:	0
Number of unknown dust devils:	8
Total number of dust devils:	1,019
Area in which dust devils were observed:	33.8km^2 (out of 260km^2)

★ The first two weeks of June, 1986 were especially active, with 635 dust devils being observed on 10 days, 7 of these being highly active days (see definition below). The most active day was 6th June 1986, with 90 dust devils being observed in 5.5-hour period. The most active day in 1987 was 8th May, with 67 dust devils being observed in a 6.1-hour period.

★ Within two kilometers of the center of the test site (the modified area) 637 dust devils were observed; in 1987, 734 devils were observed.

★ In 1986 (1987), the average length for the period of production was about 3.74 (4.23) hours for the 57 (33) days in the three active categories. The longest active period in 1986 was about 7.5 hours with 55 dust devils (on 22nd May). The longest period in 1987 was on 8th May. The typical production period was from around 1030 to around 1430 MST.

★ Most of the dust devils had lifetimes of approximately one minute, with two lasting about nine minutes. In general, the larger dust devils had longer lifetimes.

TABLE 2: Categorization of Days By Activity Level.

For 1986

Activity Level	*Number of Days*	*Number of Devils*	*Mean Prod Time*	*Avg Cld Cvr*
High	19	1,103	3.83 hrs	0.3
Moderate	25	932	3.87	0.3
Low	13	161	3.37	0.4
Limited	4	11	0.62	0.6
Total	61	2,117		

For 1987

Activity Level	*Number of Days*	*Number of Devils*	*Mean Prod Time*
High	8	319	3.65
Moderate	17	554	4.44
Low	8	133	4.35
Limited	3	13	0.90
Total	36	1,019	

In an attempt to categorize the different levels of daily activity, the number of dust devils observed each day was plotted versus the total time of production. This scatter plot indicated that characterization of the days by four activity levels on the basis of average production rate (dust devils per hour) was appropriate: *high* (more than 15/hour), *moderate* (more than 10/hour), and *low* (less than 2.5/hour). A fourth category, termed *limited*, was established for those days with few events and short production times. The results of this categorization are shown in Table 2, which also shows the number of dust devils and mean production time for each category. The mean sky cover for the days in 1986 is also given.

On typical days with moderate or high levels of dust devil activity, the lapse rate LR31 levelled off at ca 0.25 °C m^{-1} at about the same time the first dust devils were observed. Subsequent values would then fluctuate about this mean value until 1500 to 1600 hours, when LR31 would begin to decrease.

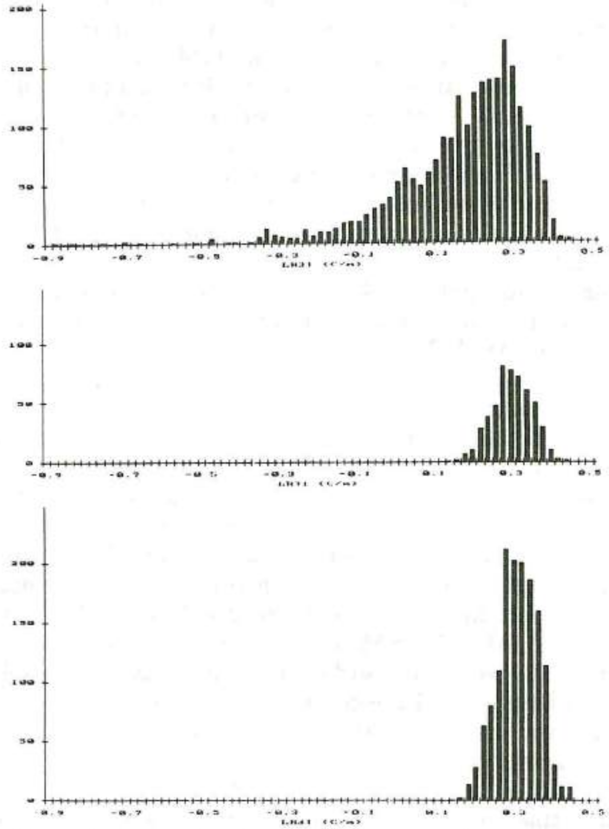


Fig.3: Histograms showing (a) the frequency of occurrence of daytime LR31 values in 1986, and (b) intervals with dust devils and (c) the number of dust devils associated with the intervals in (b) as functions of LR31. The class interval is 0.02 °Cm^{-1} in all cases. See text for details.

Most dust devils occurred when the 10-meter wind speeds were between 2.5 and 3.5m s^{-1}. There did not appear to be a favoured wind direction. Dust devil activity tended to decrease as the wind speed increased, although nine devils occurred when the 10-meter wind speeds were between 9 and 10m s^{-1}. There were also few dust devils at very low wind speeds.

Analysis of the 10-meter wind direction indicates that there apparently was not a favoured direction associated with the periods when dust devils were observed. We interpret this to mean that the whirlwinds we observed were a local product of the convective process, and not the result of flow around some local topographic feature.

Analysis of the sky cover observations indicates that days catagorized as high and moderate in activity invariably had at least their mornings with 0.1 or less sky cover. High and moderate activity days that had long productive periods had clear skies until late in the afternoon. Low and limited activity days were generally associated with high levels of cloudiness for most of the day (and attendant precipitation in many cases). These points are reflected in the daily average sky cover for the 1986 observing period shown in Table 2.

To illustrate the inter-relationships between LR31 and the occurrence of dust devils, we will focus now on the events of 6th June 1986, the most active day during the two observing periods. Fig.4a shows the evolution of this lapse rate for 6th June 1986, while Fig.4b shows a time section (constructed by interpolation between the measured values) of the temperature in the layer from surface to 10 meters. Fig.4c shows the time sequence of the number of dust devils observed by 15-minute interval.

Reading from left to right, Figs.4a and 4b initially show a radiation inversion that developed during the night and which persisted for about an hour after sunrise (approximately 0500 MST). The subsequent positive fluxes of sensible heat and upwelling long-wave radiation eroded the inversion from the surface upward. By 0600 MST the inversion had been eliminated in the lowest 10 meters, and this region then quickly becomes superadiabatic. The layer became very unstable over the next few hours, with the lapse rate between the surface and 0.5 meter becoming thousands of times larger than the dry adiabatic lapse rate.

On 6th June, dust devils were first observed at 1015 MST. At this time LR31 is about 0.25 °C m^{-1}. 6th June was unusual in that the mean lapse rate continued to slowly increase through most of the afternoon, reaching a maximum of 0.38 °C m^{-1} at 1430 MST. The last dust devil was observed at 1580 MST, at which time the lapse was 0.21 °C m^{-1}. After 1745 MST, the surface inversion began to redevelop. By sunset (about 1909 MST), the surface inversion was well established.

Our general findings parallel and confirm many of those obtained in the 1960's and early 1970's, though the details vary somewhat, probably reflecting site dependency. We now close with a few brief conjectures and speculations.

The occurrence of a "critical value" of LR31 ca 0.25 °C m^{-1} suggests that the usual situation is that the surface boundary layer reaches a certain degree of instability, and is then prevented from destabilizing much further by the convective mode that gives rise to dust devils. However, it also appears that under very favourable conditions, with strong solar heating, the lapse rate can increase significantly beyond this value. The rate of production of dust devils appears to

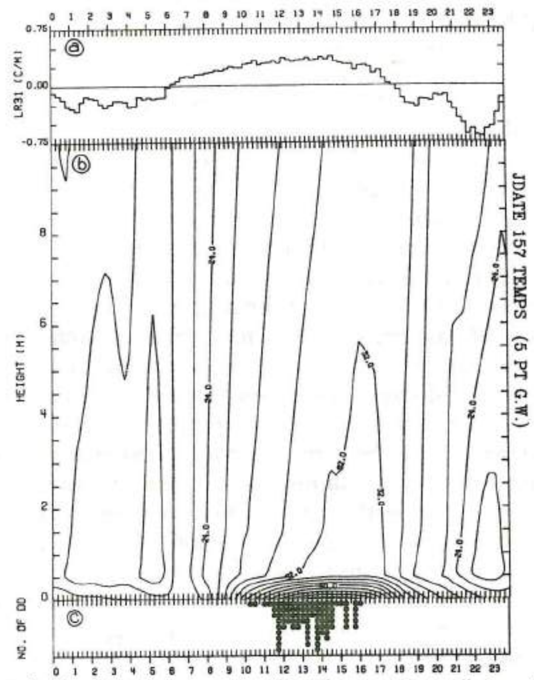


Fig.4: A display of temperature data for 6th June 1986. All times in MST. (a/top panel): A time series plot of lapse rate LR31 computed directly from the 15-minute average values of 0.5 and 10m temperature. The dots mark sunrise, solar noon, and sunset. (b/middle panel): A time section of the temperature (°C) in the layer from surface to 10m (see text for details of how this plot was constructed). (c/lower panel): Distribution of observed dust devils by 15-minute intervals. Each dot corresponds to 1 dust devil.

increase rapidly even for small increases in the laspe rate above about 0.25 °C m^{-1}.

The very active period in early June, 1986 was apparently due to strong insolation combined with generally dry conditions and little cloudiness. Such conditions maximize the warming of the lowest 50 meters or so via sensible heat flux and upwelling long-wave radiation. As late June approached, afternoon thundershowers became prevalent as the "South-west monsoon" established itself. Morning solar heating was reduced by residual cloudiness and the warming effects of upwelling long-wave radiation were confined to the lowest few meters due to the higher moisture content of the air. By July, afternoon thunderstorms were the rule so that dust devil activity was usually restricted to late mornings and early afternoons. With increasing cloudiness, dust devil production dropped rapidly and often terminated abruptly. If it rained during the night, the beginning of the active period was delayed the next day due to evaporation of water from the soil.

Our most striking finding is the drastic change in the spatial distribution between 1986 and 1987. We speculate that the 1986 maximum is at the natural center of activity for this region. We suggest that all the site preparation work on

Ground Zero changed the characteristics of the surface significantly and likely allowed the soil and surface temperatures to reach higher maximums as a result. We conjecture that the net effect of all the surface modification resulted in Ground Zero becoming in 1987 the regional hot spot, one with a nearly continuous thermal rising above it. It then drained most of the highly unstable air into this area and so led both to the suppression of dust devil activity elsewhere and to the shift in the maximum right over Ground Zero.

Grading and vehicle traffic on Ground Zero provided more dust to be lofted by the dust devils, making those which occurred there very visible. This may be connected to the interannual difference in distribution with estimated size to be seen in Table 1. A more subtle effect of the dust may have been to act as a blanket of very low thermal conductivity. A few measurements with a handheld radiometer indicated that the top of a thick covering of dust was about 5 °C warmer than bare soil/caliche surfaces only a few meters away.

A finding that is perhaps associated with this conjecture is that the mean production period (for days in the three most active categories) was approximately one-half hour longer in 1987. It should be recalled that the observing period in 1987 was in the spring, while the 1986 period bracketed the summer.

Why the area to the west of the junction of Route 1 and 13 should be the natural center for dust devil activity in this region is not at all clear. In this area, the surface is almost bare, except for a moderately dense (by arid region standards) covering of creosote bushes. These are a dark green in color. Perhaps they cause a natural hot spot to appear in this area.

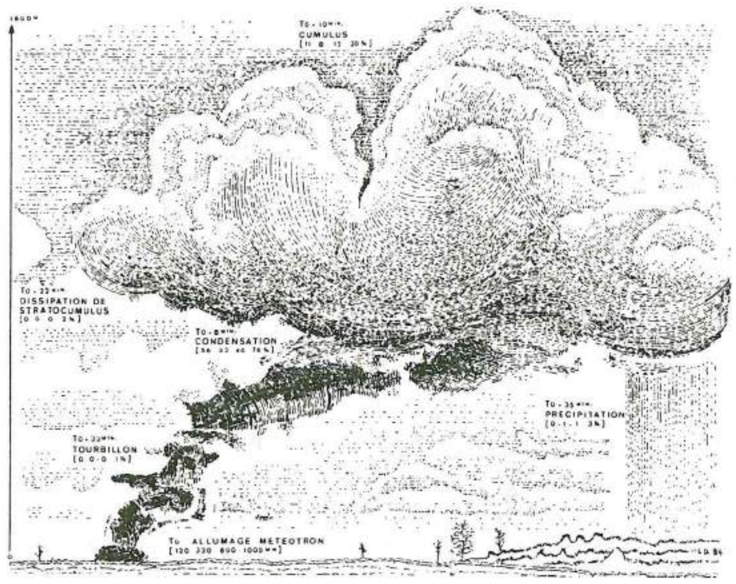
How do we account for the visibility of dust devils seen in areas where the surface contained little apparent dust? We speculate that given a surface, a dust devil can produce a significant amount of dust. It can do so directly, by abrading the surface through strong surface stresses (laboratory models suggest that the strongest wind speeds are very close to the surface). It can also do so indirectly, as particles too large to be lofted very high are continuously recirculated in the inflow at the base of the whirl. These bounce around the base of the core, loosening surface material with every impact.

LA CONVECTION ATMOSPHÉRIQUE ET SA SIMULATION
(ATMOSPHERIC CONVECTION AND ITS SIMULATION)

J. DESSENS, B. BENECH et C. CHARPENTIER

(16mm colour film, duration 32 minutes, English version)

Résumé: Ce film, réalisé par le Service du Film de Recherche Scientifique en collaboration avec l'Observatoire du Puy de Dôme et Electricité de France, a pour objet l'étude des panaches thermiques et des nuages produits par des surchauffes locales de l'air au voisinage du sol ("météotrons"). La partie introductive présente la convection thermique dans l'atmosphère par simulation en milieu fluide, par cinématographie à cadence lente sur des cumulus naturels isolés, et par animation. La partie expérimentale décrit un programme d'étude de la convection artificielle avec le Météotron, système de brûleurs à l'air libre pouvant développer une puissance calorifique de 1000 MW pendant plusieurs dizaines de minutes; trois séries de 12 expériences chacune réalisées en 1978 et en1979 dans des conditions météorologiques variées ont permis de classer en quelques types les panaches de fumée et les nuages provoqués; la séquence la plus spectaculaire de cette partie du film montre, en images du ciel total, la pénétration d'un panache dans une couche uniforme de stratocumulus, la surcondensation dans le volume nuageux pénétré, puis la dissipation de la couche de stratocumulus dans une zone annulaire environnante. Enfin, la partie théorique du film introduit le jumelage des résultats expérimentaux obtenus à l'aide du Météotron avec des modèles numériques destinés à la prévision des effects météorologiques d'une surchauffe du sol d'origine naturelle ou artificielle.



HAILSTORMS AND INTENSE LOCAL RAINFALLS IN THE BRITISH ISLES

By JONATHAN D. C. WEBB
Tornado and Storm Research Organisation, Oxford

Abstract: This paper discusses the important aspects of recent TORRO research into damaging hailstorms, including the TORRO Hailstorm Intensity Scale. The significance of related TORRO research on heavy rainfalls is also highlighted. The types of cumulonimbus responsible for exceptional rain and hailstorms are discussed with reference to documented British cases. The current hailstorm database is examined; a very extensive data set of severe storms has already been assembled and this is summarised in some detail to investigate synoptic, geographical and seasonal features.

TORRO HAILSTORM DIVISION AND THE TORRO HAILSTORM INTENSITY SCALE

During the past three years TORRO has proceeded with an extensive programme of research into the incidence of damaging hailstorms in Britain. This has resulted in a current databank of well over 1,000 such cases.

An important development, which has assisted the direction of current and historical research, has been the proposal and implementation of the TORRO Hailstorm Intensity Scale. This scale was first introduced in 1986 (see *J. Meteorology*, vol.11, no.114, pp.337-339). Subsequent continued testing has necessitated a few minor changes and the revised scale is presented in Table 1a. All reports of true hail (precipitation in the form of hard ice particles 5mm diameter or more) are recorded as at least H0. H1-H10 reflect increments of damage related to the size (Table 1b) and intensity of the hail and the strength of accompanying winds. Examples of the application of this scale are included in the annual hailstorm reports for 1984-86 published in the *Journal of Meteorology* (Webb and Elsom, 1986 and 1987, Webb, 1988).

TABLE 1a: TORRO HAILSTORM INTENSITY SCALE.

TORRO Intensity	*Description of Probable Damage*	*Range of likely Size of Hailstones (code)*
0	True hail of pea size but no damage.	1
1	Leaves holed; flower petals cut.	1-3
2	Leaves stripped from trees and plants; vegetables, fruit and crops bruised and scarred; Vegetable leaves shredded.	1-4
3	A few panes in glasshouses, cloches and/or skylights broken; wood (fences) scored; paint scraped off window ledges; caravan bodywork dented; perspex roofing holed; canvas (e.g. tents) torn; stems of crops severed and seeds threshed; fruit sliced/split.	2-5
4	Some house windows and/or vehicle windscreens broken/cracked; glasshouses extensively damaged; some felt roofs pierced; paint scraped off walls and vehicles; some thin car bodywork visibly dented; small branches broken from trees; unprotected birds and poultry killed; firm ground pitted.	3-6
5	Some roof slates and pottery-type tiles broken; many windows smashed; plate-glass roofs and reinforced glass windows broken; bodywork of most exposed cars visibly pitted; bodywork of light aircraft pitted; risk of serious or fatal injuries to small animals; strips of bark torn from trees; woodwork pitted and splintered; large branches cut from trees.	4-7
6	Many roof slates and tiles (excepting concrete) broken; shingle and thatch roofs breached; corrugated iron and some sheet metal roofs scored and a few holed; brick walls slightly pitted; wooden window frames broken away.	5-8
7	Slated, shingle, and many tiled roofs shattered, exposing rafters; metal roofing punctured; brick and stone walls pitted; metal window frames broken away; bodywork of cars and light aircraft seriously/irreparably damaged.	6-9
8	Concrete roof tiles cracked; sheet metal, slated, shingle, and other tiled roofs destroyed. Pavements pitted; bodywork of commercial aircraft severely damaged; small tree trunks split apart; risk of serious injury to persons caught in the open.	7-10
9	Concrete walls pitted; concrete roof tiles widely broken; walls of wooden houses completely holed; large tree trunks cut down; risk of fatal injury to persons caught in the open.	8-10
10	Wooden houses destroyed; brick-built houses very severely damaged; risk of fatal injury to unprotected persons.	9-10

TABLE 1b.: RELATIONSHIP OF HAILSTONE SIZE TO TORRO HAILSTORM INTENSITY.

Size Code	*Diameter mm*	*Description*	*Intensity Range*
1	5-10	Pea.	0-2
2	11-15	Mothball, bean, hazelnut.	0-3
3	16-20	Marble, cherry, small grape.	1-4
4	21-30	Large marble, large grape, walnut.	2-5
5	31-45	Chestnut, pigeon's egg, golf-ball, table-tennis ball, squash ball.	3-6
6	46-60	Hen's egg, small peach, small apple, billiard ball.	4-7
7	61-80	Large peach, large apple, goose egg, small/medium orange, tennis ball, cricket ball, baseball.	5-8
8	81-100	Large orange, grapefruit, softball.	6-9
9	101-125	Melon.	7-10
10	over 125	Coconut, etc.	8-10

Inevitably, much time to date has been spent on retrospective research, but the resulting large database has provided us with a solid foundation to launch investigations into where, when, and why damaging hailstorms occur in the British Isles. If research has not yet provided all the answers, it has certainly posed some interesting questions!

RELATED RESEARCH ON HEAVY RAINFALLS

It was noted in an earlier paper (Webb, Elsom and Meaden, 1986) that the occurrence of damaging hail is closely linked to that of overhead thunderstorms. Another related line of research will focus on the incidence of intense short-duration rainfalls. Two recent papers in the Journal (Pike 1987, Prichard 1987) have highlighted the importance of this topic. It is hoped that a TORRO Heavy Rainfalls division can resume the regular documentation of extreme rainfall events which for many years had been published in the appropriate sections of *British Rainfall.* Moreover, TORRO plans to co-ordinate its research into lightning strikes, hail and point rainfalls with a view to an improved understanding of the behaviour and spatial distribution of all severe convective storms. To illustrate the possible intensities of thunderstorm rainfall that Britain can be subjected to, Table 2 notes some extreme rainfalls to date in specific short periods. Even this brief list of the most extreme events suggests some interesting lines of research. For instance, is it significant that practically all the locations are adjacent to local high ground?

TABLE 2: SOME EXTREME RAINFALLS FOR SPECIFIED SHORT DURATIONS IN THE BRITISH ISLES, 1870 TO DATE.

Duration in Minutes	Amount of Rain mm	Location	County	Date
5	32	Preston	Lancashire	10 August 1893
10	42	Wisbech	Cambridgeshire	27 June 1970
15	56	Bolton	Greater Manchester	18 July 1964
20	63	Sidcup	Kent	5 September 1958
20	63	Hindolveston	Norfolk	11 July 1959
30	80	Eskdalemuir	Dumfries & Galloway	26 June 1953
45	97	Orra Beg	Antrim	1 August 1980
60	97	Orra Beg	Antrim	1 August 1980
60	92	Maidenhead	Berkshire	12 July 1901
75	102	Wisley	Surrey	16 July 1947
90	117	Dunsop Valley	Lancashire	8 August 1967
105	136*	Hewenden Reservoir	West Yorkshire	11 June 1956
105	116	Sevenoaks	Kent	25 June 1980
120	155	Hewenden Reservoir	West Yorkshire	11 June 1956
150	164*	Hampstead	Greater London	14 August 1975
180	178*	Horncastle	Lincolnshire	7 October 1960

*Asterisk denotes estimation from fall of longer duration.

TYPES OF SEVERE CONVECTIVE STORM

Nearly all reports of significant hail are associated with thunderstorms, and, as with the latter (Prichard 1985), there are countless synoptic situations involved. However, two types of severe thunderstorm responsible for many incidences of damaging hail and exceptionally intense rainfalls can be recognised.

1. Slow-moving, locally-induced storms. Conditions for these are favourable when the atmosphere is unstable (i.e. cold air aloft and relatively warm moist surface air) but when both the surface and upper winds are fairly light. Vigorous cumulonimbus clouds forming under these conditions may develop into multicell storms as new cells are triggered by the downdraughts of existing cells. Such storms usually develop in a somewhat unorganised manner although a pattern of new cell development may emerge which is related to surface geographical features, primarily high ground. A notable example of this occurred in the Hampstead storm of the 14th August 1975, when about 169mm of rain fell in 2 hours 35 minutes. Other slow-moving thunderstorm systems of this kind, where high ground probably assisted in maintaining the storm, include the Lincolnshire deluge of 7th October 1960 when 178mm of rain fell in 3 hours at Horncastle (at the foot of the Wolds), and a very localised downpour in the East Shropshire hills on 22nd July 1972, when 160mm of rain fell in 4½ hours at Ratlinghope.

Besides the exceptional falls of rain that can occur, such quasi-stationary storms can also be responsible for intense and prolonged falls of hail, sometimes giving remarkable accumulations on the ground. During a slow-moving thunderstorm at Sevenoaks, Kent, on 25th June 1980, 116mm of rain fell in 105 minutes; much of the precipitation was in the form of pea-sized hail which lay to a depth of 150mm or more. Quite large hailstones may form when the small hail pellets generated in one storm cell become caught in the updraught of a newly developing cell with consequent growth over an extended period. Again, this is perhaps more common when surface relief and/or some degree of vertical wind shear imposes a favoured position for fresh cells to be triggered and subsequently move through the storm. Intense hail up to about 20mm diameter accumulated to some depth during the Hampstead storm and hailstones up to about 30mm in diameter (walnut size) fell at Moel Cynedd, Mid Wales, on 15th August 1977, when a local 2½ hour storm produced 98mm of rainfall (Newson 1977).

Many hailstorms of TORRO intensity 1 to 4 are associated with the above type of convective storm.

2. Severe travelling storms occur when there is a significant vertical wind shear, usually with quite strong upper winds. Such an environment enables a cumulonimbus system to develop an organised updraught/downdraught structure (see Ludlam 1961 and 1980, Browning and Ludlam 1962, Browning 1978). Since these storms moved more rapidly than the earlier mentioned category, precipitation is less prolonged in any one place; however, it is often extremely intense. A typical pattern of development for such storms involves the propagation to the right of the medium-level steering wind as new cells regularly develop on the forward right flank of the storm. The latter is the point where the low-level inflow meets the downdraught squall front which, because of anticlockwise rotation in the Northern Hemisphere, sweeps round the right flank of the storm. The organised development and movement of cumulonimbus cells through the storm makes possible the growth of very large hailstones, 40mm diameter or more, which may have been grown in several successive cells.

In the most extreme cases of organised convection, usually when there is very strong directional wind shear, a single giant cumulonimbus *supercell* may develop. The structure of these supercell storms allows for a continuous inflow of warm surface air to feed the updraught at the front of the storm, and a corresponding supply of cold (or potentially cold, i.e. dry) medium-level air drawn into the storm's rear to reinforce the downdraught. The extremely vigorous and persistent updraughts enable hailstones to grow to exceptional sizes, sometimes 75mm diameter or more. The precipitation-cooled downdraught forms a squall front which sweeps round the right flank of the storm. Tornadoes may be spawned at the point where the advancing gust front lifts the inflowing warm air to boost the updraught (Meaden 1985a). Again, maximum convergence on this right flank deviates the storm path to the right of the medium level steering wind.

The anvil dome of a supercell storm extends horizontally over a vast area, while its top often overshoots the tropopause; an aerial photograph of the 1984 Munich hailstorm revealed a cloud tower some 100 kilometres wide and extending up to at least 12 kilometres in height. A recent storm in north-west Bavaria on 18th September 1987 (accompanied by hailstones up to 80mm diameter) was attributable to a single convective cell, which soared 18 kilometres high. It is scarcely surprising that the approach of severe hailstorms is often marked by intense "day darkness" at ground level.

Organised convective storms, whether of the multi-cell or the supercell type, are referred to as self propagating storms, because the required vertical wind shear enables the updraught and downdraught to co-exist. It is likely that all severely damaging hailstorms (H5 intensity or more) are of the self-propagating variety.

Recent British examples of quite organised multi-cell storms, both of which produced hail up to 40mm diameter, include the Berkshire storm of 23rd July 1984 (see *J. Meteorology*, vol.12, pp.120-121) and the Essex/Suffolk storms of 22nd August 1987. The South Coast hailstorms of 5th June 1983, were a classical outbreak of self-propagating storms. A series of organised multi cell storms tracked along the coastal belt of Dorset, Hampshire and Sussex, accompanied by hailstones up to at least 50mm in diameter; some of the storms probably devloped into 'severe right supercells' (Rowe and Mortimore 1984, Hill 1984). Two days later severe storms affected Western Britain; some developed into supercells, producing hail of 50-75mm diameter in North Wales and North-West England (Dent and Monk 1984).

SEVERE HAILSTORM PREDICTION

The successful fore casting of these severe travelling hailstorms depends on predicting:

1. Favourable general atmospheric conditions over a region, i.e. strong vertical wind shear and potential instability.
2. Particular features on the surface and/or upper air synoptic charts which might act as convergence zones and unleash potential instability.
3. Local factors such as topography and temperature differentials which can directly or indirectly influence storm development.

Synoptic convergence zones include: (a) *Slow-moving frontal systems,* as on 1st-2nd July 1968, when a waving front was situated over western England and Wales. On that occasion very hot surface air had been drawn into central and south-east England. Strong upper southerly winds carried a succession of severe thunderstorms northwards over western Britain, several being distinguished by very large hailstones. (b) *Well-defined thundery troughs.* These usually precede a surface cold front, sometimes heralding the front at higher levels. Thundery troughs which move north-east embedded in a strong south or south-westerly upper flow have particular potential for severe hailstorm development. They indicate zones of enhanced instability, while the backing of the surface winds ahead of the trough accentuates the directional wind shear. An excellent example occurred on 14th July 1975, when a destructive hailstorm moved north-east across the Birmingham area, Staffordshire and Nottinghamshire. Another such trough was responsible for the storm of 30th May 1897, which swept rapidly across Sussex and Kent (Table 5). (c) *Thundery cold front or squall lines.* These are responsible for a few widespread outbreaks, e.g. on 22nd September 1935 when a depression moved from Biscay to Lincolnshire and severe hail squalls marked the passage of the cold front in the Midlands (Table 5). Several multiple tornado outbreaks have occurred on these thundery cold fronts, although the two largest on record (Rowe 1985) were associated with thunderless line squalls which, in contrast, do not have sufficient depth of cloud for large hailstone development. (d) Some self-propagating hailstorms may be clustered together in small cyclonic disturbances rather similar to *tornado cyclones* (Meaden 1985). These systems are liable to run along pre-existing frontal convergence zones. The 'tornado cyclone' of 21st May 1950 (Lamb 1957) was accompanied by falls of hailstones up to 50mm in diameter

in Buckinghamshire and Bedfordshire. On 4th July 1915 a swath of devastating hail and squall damage was reported from North Devon to Oxfordshire, in the wake of a small depression which travelled east-north-east across Southern England. Destructive storms on 16th July 1947 were attributable to the passage of a small depression northwards from near Brighton to the Norfolk coast. Besides the phenomenal downfall of rain (and grape-sized hail) at Wisley, Surrey (Table 2), golf-ball sized hailstones left a trail of devastated crops and damaged property across mid-Suffolk (Table 5).

It must be stressed that even against the background of a well-defined convergence zone coupled with a strong vertical wind shear, local topography still cannot be ignored when considering where storms will actually break out. Hill (1984), for example, suggested that the explosive development of the June 1983 south-coast hailstorms may have been attributable to the nature of the South Devon coastline, which could have impeded the low-level north-easterly windflow and have increased the depth of cold air.

In the absence of a conspicuous synoptic convergence zone, local factors which can trigger thunderstorm development will again be paramount. These will include both surface relief and the distribution of surface temperature. Table 5 confirms that almost all severe hailstorms in the British Isles move from between south and west in accordance with our prevailing upper winds. Much consideration, when forecasting, will have to be given to areas that are situated 'downwind' of a spawning ground for such storms. The great Wiltshire hailstorm of 13th July 1967 appears to have been initiated over the Mendip Hills in Somerset, and to have subsequently moved north-north-eastwards with the quite strong upper wind. On both 5th July 1985 and 22nd August 1987, severe hailstorms in East Anglia could be traced back to explosive initial thunderstorm development over the zone of highest surface temperatures in north-east Hampshire and the London area. In both cases the storms reached Essex and East Anglia at the time of day when a sea-breeze front might have formed a distance inland and given additional impetus to convective activity. The locally severe Berkshire storm system of 23rd July 1984 originated in cumulonimbus development near a sea-breeze convergence zone over Southern England.

TABLE 3: (a) Average annual number of days with reports of damaging hail for each pentad 1866-1985.
(b) Number of destructive hailstorms (H5 intensity or more) for each pentad 1866-1985.

Pentad	*(a)*	*(b)*	*Pentad*	*(a)*	*(b)*	*Pentad*	*(a)*	*(b)*
1866-1870	7	2	1906-1910	11	4	1946-1950	12	4
1871-1875	10	2	1911-1915	10	5	1951-1955	8	1
1876-1880	9	3	1916-1920	3	3	1956-1960	10	3
1881-1885	10	3	1921-1925	4	2	1961-1965	6	1
1886-1890	11	4	1926-1930	3	2	1966-1970	6	3
1891-1895	13	4	1931-1935	4	3	1971-1975	7	1
1896-1900	10	8	1936-1940	14	3	1976-1980	10	1
1901-1905	9	2	1941-1945	9	2	1981-1985	14	5

ANNUAL FREQUENCIES OF DAMAGING HAILSTORMS

Table 3a gives the *average* annual number of days with damaging hail reported in the U.K. and Ireland for each pentad during the 120 years between 1866 and 1985. These frequencies largely reflect variations in the *reporting* of hailstorms (and the periods of rapid progress in hailstorm research!). Reports drop sharply from 1915 with the cessation of extensive observer's notes in *British Rainfall* and the *Meteorological Magazine.* Recording improves noticeably again from 1935 as a result of the extensive data received by the Thunderstorm Census Organisation, and once again from 1975 with the establishment of TORRO.

If we concentrate on the results from periods of effective reporting such as 1871-1910, 1935-1950 and 1975 onwards, it becomes clear that significant hailfalls (i.e. those heavy enough to damage vegetation, fruit or crops) must occur on between 10 and 20 days per year in the British Isles (occasionally more?). This assessment takes account of the likelihood of further events coming to light for past years.

It may be noted that a survey by the Meteorological Office in 1956 (*Met. Mag.,* vol.85, pp.344-346), based on reports published in *British Rainfall* and the *Meteorological Magazine,* suggested that hail damage had only been reported on an average of 3-4 days per year between 1906 and 1955. This unrealistically low assessment highlights the marked decline in reporting in those publications after 1914.

As with tornadoes, we would expect the severest events to be more consistently reported over the years. This is strikingly evident when one examines the five-yearly *totals* of severely damaging hailstorms (intensity H5 or more) between 1866 and 1985. The reporting of these 'destructive' storms displays little tendency to be affected by variations in the general documentation of hailstorms. There is no significant trend in evidence, although it is worth emphasising that the majority of years in this period had at least one 'destructive' storm (one causing severe damage to glass and other structures). Fortunately the data available on severe storms is now reasonably comprehensive, right back to about 1660; in fact, three severe storms can be cited for a historical year like 1697, which is comparable with the most on file for any one year during the period analysed in Table 3.

GEOGRAPHICAL DISTRIBUTION OF SEVERE HAILSTORMS

We will focus on the geographical distribution of the really severe storms, since we currently have a more complete and longer term data set available. Fig.1 maps the number of known such storms (estimated H5 intensity or worse) affecting each county of Great Britain from 1660 to date. Owing to more limited data, figures are not given for Ireland, although it is hoped to include these at a later date. Naturally, when reviewing Fig.1, some account must be taken of the size of each county, although the impact of this may be partly offset by lower population densities in some of the larger ones. As with tornadoes (Elsom 1985), the highest risk of severe hail damage appears to be in the London area, East Anglia and adjacent parts of Eastern England. Suffolk heads the 'league table' with at least 12 severely damaging hailstorms over the past 327 years. Although this might theoretically 'average out' at one severe storm there every 25 years or so, historical occurrences are far from that regular. For example, three particularly disastrous hailstorms ravaged Suffolk in the space of six years during the 1940's (June 1942, July 1946, July 1947), while two have affected Essex within the past three years!

Fig.1: Number of severely damaging hailstorms reported for each county 1660-1987 (TORRO intensity H5 or more).

The fairly high number of severe storms reported in Devon and Somerset may mirror the tendency for high ground to initiate storm development. Some severe storms affecting this area undoubtedly break along convergence fronts separating adjacent cooler Atlantic air from hot continental air that has spread north-westwards into Britain. In conjunction with a strong southerly flow at 500 millibars, a succession of severe thunderstorms ran northwards across south-west England and Wales on 1st-2nd July 1968; several were accompanied by very large hailstones. A rather similar synoptic situation was associated with widespread hailstorm damage in the region of 17th-18th July 1926.

The comparatively high totals in Lancashire and West Yorkshire suggest the influence of the Pennines as a catalyst for storm development. The low totals in Scotland partly reflect low population densities, but also the less frequent incursions of hot tropical air masses and the fewer number of cold fronts that pass over (c.f. lower tornado frequencies as described by Elsom 1985). Provisional data for Ireland, based largely on TORRO's data collection since 1975, indicate that hailstorms are probably more frequent there than in Scotland on account of the greater influence of frontal convergence zones (e.g. in June 1986).

SEASONAL DISTRIBUTION OF DAMAGING HAIL

Table 4a shows the *percentage* of all known hailstorms occurring in each month of the year since 1866. Table 4b gives similar monthly values for all severely damaging storms (H5 or worse) in the longer historical perspective back to 1660.

Reports of hail damage rise abruptly in spring (4a). This is attributable to the increased solar insolation overland and also to the relatively high frequency of northerly winds advecting cold unstable air masses at the time of year. The peak frequency for damaging hailfalls appears to be in June and July coinciding with the period of maximum solar insolation. The apparent marked decline of hailstorm-day frequencies in August is rather surprising since the average number of days with thunder reported is almost identical to that observed in June or July (see recent T.C.O. annual reports). There may be a physical explanation (i.e. higher mean upper air temperatures in August?) or this could be an anomaly resulting from the fluctuations in reporting mentioned earlier, and the relatively short period under discussion. More research is essential before such an observation can be confirmed.

TABLE 4a: % of damaging hailstorms occurring in each month of the year in the British Isles.
Based on current TORRO database of 1,061 storms during the period 1866-1986.

January	*February*	*March*	*April*	*May*	*June*
3%	2%	4%	8%	15%	21%
July	*August*	*September*	*October*	*November*	*December*
19%	13%	6%	4%	3%	2%

TABLE 4b: % of severely damaging hailstorms (H5 or more intensity) occurring in each month of the year.
Based on TORRO database of 146 severe storms during the period 1660-1986.

January	*February*	*March*	*April*	*May*	*June*
1%	0%	0%	1%	15%	21%
July	*August*	*September*	*October*	*November*	*December*
34%	19%	4%	1%	2%	2%

Table 4b suggests a tendency for the really severe hailstorms to reach a peak frequency rather later in the season, more closely in line with the annual curve of surface temperatures. This feature is more conspicuous when we examine the monthly distribution of the most extreme (H6 or worse) storms catalogued in Table5. 24 of these 35 events occurred in July or August, although, as a cautionary note, two of the most disastrous ever storms were in May 1697! Possible reasons for a high-summer peak in the incidence of very severe storms are the maximum surface temperatures in July and August, and the stronger upper westerly winds normally experienced following the June "return of the westerlies".

The occasional winter hailstorms mainly affect coastal areas; they are typically a product of vigorous convection when cold air masses cross the warm seas surrounding the British Isles. It is hoped that TORRO's drive for more thunderstorm observers in remote parts of the west and north will enable us to monitor more accurately the incidence of winter hail. Evidence strongly suggests that western parts of Scotland and Ireland are particularly affected.

Away from these windward coasts, thundery cold fronts or troughs account for most instances of damaging hail during the winter half year (October-March). Widespread outbreaks on winter cold fronts include those of 8th February 1906 and 25th October 1937; on the latter date an exceptional T7 tornado hit South Kelsey in Lincolnshire (Rowe 1985). The two most severe winter hailstorms to have affected Southern Britain this century were spawned by thundery troughs within mild but highly unstable returning maritime polar airstreams. On 5th November 1955, hailstones up to about 40mm diameter caused severe damage to windows, caravans and other structures south and east of Cambridge. On 13th December 1978, hail over 30mm diameter fell in SouthDevon breaking windows and plastic roofing as well as denting cars (Owens 1980).

MONITORING THE DEVELOPMENT OF HAILSTORMS

During recent years radar and satellite imagery have been increasingly used to monitor the progress of rain areas. This is through the remote sensing of cloud top temperatures and precipitation intensities (for *Frontiers Programme* see Browning 1986). While the type of precipitation cannot be specifically inferred from such displays, "rainfall" intensities in excess of about 100mm per hour are strongly suggestive of heavy hail (in any case, rainfall of this intensity merits note-taking). This was confirmed during analysis of radar pictures of the storms of 22nd August 1987. Cloud top temperatures of −40°C or lower are also suggestive of favourable conditions for the growth of large hailstones which require a great depth of cloud above the 0°C level. Furthermore any cumulonimbus tops in excess of about 10 kilometres require very persistent and powerful updraughts such as can only be present in highly organised convective storms.

HOW SEVERE CAN BRITISH HAILSTORMS BE?

Table 5 provides some details of historic hailstorms in the British Isles which almost certainly reached TORRO intensity H6 or more. Fresh evidence may elevate other past storms to this category in the future.

Though fortunately rare, the very worst British hailstorms can inflict damage comparable with that sustained during the catastrophic Munich storm of July 1984, (i.e. at the H8 level). In the Munich storm the largest single hailstone officially measured, had a diameter of 95mm and weighed 300 grams. Reports of even larger stones were probably authentic, although they may have referred to aggregates. Table 5 confirms some reliable reports of hail approaching this size in the British Isles. Moreover, many of our severest hailstorms have spawned tornadoes (Essex 1897, Banbury 1935, Bedfordshire 1950, Horsham 1958, Melksham 1967). The combination of an H8 hailstorm and a powerful tornado would have potentially devastating consequences if the storm tracked across a densely populated area. Even in the absence of tornadoes, the violent squalls that are a product of self-propagating hailstorms can be quite devastating in their own right (besides ensuring that the hail hits vertical targets!). On 5th July 1985 a gust of 65 knots marked the passage of a severe hailstorm over Coltishall, Norfolk; during the hour of the squall the *mean* wind was only 6 knots.

CONCLUDING REMARKS

This article has concentrated on the results of research into the most severe hailstorms. Continued expansion of our files is anticipated and this will enable us

TABLE 5: CATALOGUE OF EXCEPTIONAL HAILSTORMS REPORTED IN THE BRITISH ISLES.

Date	*Counties*	*Areas Affected*	*Size/Weight of Hailstones*	*Damage*	*Max. TORRO Intensity*
1565 July	Essex	Chelmsford area		Tiles, barns, chimneys, church windows, church battlements, all beaten down	H6
1666 July 28	Suffolk	Aldeburgh area	Turkey's eggs Weighed 1lb 2oz(?) Nearly 100mm diam.		H6+
1697 May 10	Clwyd Merseyside Lancashire	90-100km swath from St. Asaph to Blackburn. Severest damage between Bootle and Ormskirk.	40mm diam. (Clwyd) 8-12oz (Merseyside) Duck/Goose eggs (Lancs) 70mm diam. (Lancs) 5oz (Lancs)	Tiles broken. Thatched roofs breached. Nearly all west facing glass destroyed (Ormskirk). Ground ploughed-up and defaced. Samll animals killed. Severe human injuries.	H7
1697 May 15	Hertfordshire	Hitchin/Offley	60mm diam. (Hitchin) about 110mm (Offley) (Some reputed to be 140mm).	At least one human fatality (Offley). Ground torn-up. Great oak trees split. "7,000 quarries" of glass in house broken.	H8
1719 July 14	Staffordshire	Seighford (Stafford)	About 80mm diam.		H6+
1738 Aug. 5	Greater London Hertfordshire Bedfordshire Suffolk	25km swath West London – Herts.	"Larger than walnuts"	Roof tiles damaged, people injured (Uxbridge). Church windows shattered (Bungay).	H6
1761 Aug. 5	Northamptonshire	Benfield	"Weighed one pound each."	Windows broken eveywhere.	H6+
1763 Aug. 19	Kent	65km swath 5-7km wide Tunbridge Wells to Isle of Sheppey	About 80mm diam. (Wateringbury, Nettlested). 70mm diam. (Barming)	Windows, tiles broken to pieces. Bark very wounded and torn. Walls battered. Birds and small animals killed.	H7

Date	*Counties*	*Areas Affected*	*Size/Weight of Hailstones*	*Damage*	*Max. TORRO Intensity*
1797 Aug. 18	Devon			Windows shivered into fine powder. Trees broken. "Masses of hail buried 1.5 metres into ground.	H6+
1800 May 4	Leicestershire Northamptonshire Lincolnshire	65 kilometres-long swath (about 6km wide) Kettering to Stamford.	"Pigeons eggs" average 25mm diam. Largest 40mm diam.	Church windows shivered. South and south-west facing windows demolished. Cow killed (Laxton).	H6
1800 Aug. 19	Oxfordshire Buckinghamshire Bedfordshire	60 kilometres long, 8km swath. Upper Heyford (Oxon) to Clophill (Beds).	Hens eggs (Oxon). 50-75mm diam. (Bucks). Up to 80mm diam. (Beds).	Lead window frames broken (Clophill). Much damage to leaden roofs (Ampthill). 6cm holes in ground. Nearly all windows in south-east of town broken (Crawley).	H7
1818 July 24	Orkney Islands	Stronsay, Sanday. 32 kilometres long 2-3km wide swath.	"Goose eggs"	All exposed windows broken. Wooden window frames broken away. Hailstones buried deep in ground. Cattle severely injured.	H6
1843 Aug. 9	Oxfordshire (Possibly same storm that affected Cambridgeshire, Bedfordshire and Norfolk)	26 kilometre swath Kingham – Aynho.	Average 50mm diam. Max. 65mm diam. or more. Average weight 2oz (Enstone).	Slate roofs pounded to pieces, new slates cut through. Leaden roof of church much indented. Bark severely torn and battered. Lead windows frames smashed (Sandford St. Martin). 50,000 panes of glass broken (Chipping Norton).	H7
1855 Aug. 23	Isle of Wight West Sussex		Hens eggs (Newport). Up to 50mm diam. (Possibly 70mm).	Hundreds of birds killed. 6.5mm thick glass shattered.	H6
1859 July 20	Berkshire Greater London (other severe storms in Yorks., Lancs, Cheshire).	East Berkshire N.W. London	Pigeons eggs or larger.	Windows of churches, chapels, other buildings destroyed (Windsor). Cattle killed. Trees beaten to pieces. All exposed windows broken (Winchmore Hill).	H6

Date	Counties	Areas Affected	Size/Weight of Hailstones	Damage	Max. TORRO Intensity
1879 Aug. 2/3	Greater London (Symons 1879)	At least 11 kilometres x 3km area of S.W. London.	25-38mm diam. Kew. 50mm diam. Twickenham. Some weighed 4 ounces.	5-8cm holes in the ground (Richmond). Zinc roof pierced. Iron roof scored "like a sledgehammer". Tiles, slates, "perforated like bullets" (Brentford). Much plate glass destroyed.	H6
1883 July 3	Lincolnshire Humberside	25 kilometres long swath Caistor – Barton-on-Humber.	About 50mm diam. At least 2 ounces (some reported up to 6 ounces).	Plate glass pounded into small fragments. Bark and branches of strong trees broken, bruised and gashed. House woodwork indented. Many small animals killed.	H6
1893 July 8	North Yorkshire (Marriott 1894)	Richmond area (severe HS also at Harrogate).	50-60mm diam. 3½ ounces.	200,000 panes of glass broken. Metal roofing punctured. Tiles and slates broken (90mm diam. fracture).	H6
1897 May 30	East Sussex Kent	80 kilometres long swath. Seaford – Gillingham.	3-4 ounces. Hen's egg to small orange size.	2½cm thick chapel windows broken (Kent). Every pane of glass in exposed cottages broken (Selmeston).	H6
1897 June 24	Berkshire Greater London Essex (Essex Field Club 1897).	125 kilometres long swath Maidenhead to to Colchester.	3½ ounces (Ingatestone). 5oz ? (Writtle). 60mm diam. (Kelvedon). 75 x 38mm (Theydon Bois).	Corrugated iron riddled (Chelmsford). Plate glass shivered. Window frames broken. Slate roofs holed. Roof tiles "broken like a hammer" (Ingatestone).	H7
1906 July 8/9	Ireland/Cork	Ballinora	"Oranges"	Bark of trees much battered and torn.	H6
1913 May 27	Cambridgeshire Suffolk Essex	About 50 kilometres long. Harston (Cambs) to Halstead (Essex).	Hen's eggs (N.W. Essex)	Thousands of windows and tiles broken. Corrugated iron riddled. Tarred felt roofing "cut to ribbons". Many small animals killed.	H6

Date	Counties	Areas Affected	Size/Weight of Hailstones	Damage	Max. TORRO Intensity
1915 July 4	Devon Somerset Avon Wiltshire Gloucestershire Oxfordshire	About 230 kilometre long track from Ilfracombe to north of Oxford (Ambrosden).	4 ounces (Ilfracombe). Hen's eggs North Wilts. Hen's eggs Somerset. Hen's eggs Oxon.	Metal pierced, bark on trees split (Wilts). Church windows broken (Avon, Oxon).	H6
1918 July 16/17	Surrey Greater London (Clark 1920)	35 kilometre long hailswath from South Holmwood to North Bromley.	Average diam. over 50mm	Many roof tiles broken (Purley). 2½cm pits in ground.	H6
1922 May 25	Greater London Kent Surrey	esp Tunbridge Wells Tonbridge areas.	20-50mm diam. average pigeon's eggs.	Galvanised iron roofing holed (Kent). Windows smashed all over town (Tunbridge Wells).	H6
1925 July 22	Greater London	Area 15-20 kilometres long and wide. Woolwich – Dartford. East Ham – Romford.	Average 50mm diam. largest size of man's fist. 8 ounces (Plumstead) ? Aggregate.	Slate roofs holed.	H6
1935 Sept. 22	Northamptonshire Oxfordshire	At least 100 kilometres long swath. Chipping Norton (Oxon) to just south of Peterborough.	Golf balls (North Oxon). 50mm diam. (Northampton). Hen's eggs (Rothersthorpe). Man's fist (Great Billing). Tennis ball (Rushden). 2 ozs (Wellingborough).	350 sheets of plate glass smashed (Rothersthorpe). Scores of slates and tiles damaged, cottage roof holed (Wilby, Northamptonshire).	H6
1945 May 11	Oxfordshire Buckinghamshire	About 35 kilometres long swath. Oxford – Buckingham.	2 ozs, golf balls (North Oxford). Ping-pong to tennis ball size (Bicester). 8¼ozs (Bicester) Aggregate ? 75 x 63mm x 38mm (Ambrosden).	Clean hole through corrugated iron roof (Bicester). Aircraft severely damaged in flight. Large branches cut down.	H6

Date	Counties	Areas Affected	Size/Weight of Hailstones	Damage	Max. TORRO Intensity
1947 July 16	Suffolk Norfolk	80 kilometres swath Sudbury – Dereham.	Golf balls "fair sized" apples. 38mm diam. Nedging Tye.	Hundreds of windows smashed. Tiles smashed. Thatch roofs damaged. Holes torn in 'stout timber'. Branches slashed off trees.	H6
1958 Sept. 5	Isle of Wight West Sussex Surrey Kent Greater London Essex (Ludlam and Macklin 1959)	Storm covered 175km path from Isle of Wight to Maldon (Essex). By far the largest hailstones in Horsham area.	Tennis/cricket balls (west of Horsham). Largest about 80mm diam. Heaviest weighed 6¾ozs (Southwater).	Roof tiles broken. Small lead window frames broken away. Thousands of windows shattered. Cars covered in dents. Airliner badly damaged in flight (south of Gatwick). 5cm deep pits in ground (Five Oaks, Southwater). Bark of trees cut and split (Kirdford). Barns, sheds, pitted and splintered.	H6/7
1967 July 13	Wiltshire Gloucestershire (Hardman 1968)	About 90 kilometres long – Mendips to North Glos.	Golf balls (Trowbridge). 50mm diam. (Melksham). 50-75mm diam. (Gastard). 50mm diam. in South Cerney.	Stained glass windows in church broken (Lacock). More than 400 windows smashed in north Trowbridge (Hilperton). Church windows broken at Holt. Thousands of window panes broken, tiled roofs damaged and dozens of cars battered (Holt to Melksham areas).	H6
1968 July 1	Devon Somerset, South and Mid Glamorgan Powys Cheshire Merseyside	320 kilometres swath of hail damage mid Devon-Merseyside, especially North Somerset and South Wales.	50-65mm Minehead. "Tennis balls" Exebridge. 75 x 60mm Ellipsoid at Rhoose airport.	7-10cm pits in ground (Minehead). Aircraft damaged (Cardiff airport). Many windows broken. (Pontypridd).	H6
1968 July 2	Devon	35-40 kilometre long swath. Start Point to Newton Abbot, especially Slapton area.	Average golf balls. Largest 50mm diam. or more. One reported to be 4ozs.	Many roof tiles broken. Brick walls covered in in pits. Corrugated iron roofs pierced. Greenhouses reduced to skeletons.	H6
1983 June 7	Powys, Clwyd Cheshire Greater Manchester Lancashire	Main swath 200km long – Central Powys – North Yorks border.	50-75mm diam. in several places.	Tiles, slates, windows smashed. Guttering holed (Greater Manchester). Much reinforced glass broken.	H6

to analyse in detail the geographical distribution of all hail events. The frequency of occurrence in each British county will be investigated adjusting the results to compensate for area. A more detailed analysis of distribution can then be made by examining each county in turn and plotting every report of damaging hail observed. The results may suggest some thunderstorm tracks, evidence for which can be supported by similar mapping of lightning strikes and/or flood damage. There also exists a substantial file on Continental European hailstorms which, as it grows will provide a basis for evaluating the relative risks throughout Europe.

The TORRO Hailstorm Scale will be extended to include a suitable formula for representing the length and breadth of hailstorm swaths. TORRO also proposes to support the scale with a set of suitable illustrative photographs.

There will be continuing research into the synoptic origins of hailstorms, attention being paid to the incidence of widespread outbreaks of damaging hail. We must also attempt to tackle such questions as why some widespread severe thunderstorms occur with little or no hail reported (e.g. on 5th-6th August 1981). With regard to this point it is interesting to note that the United States National Weather Service defines a "severe thunderstorm" as one accompanied by: hail sufficiently large enough to break windshields i.e. at least 20mm diameter; and/or winds gusting to 50 knots or more, sufficient to uproot trees and damage roofs and structures. In this country, any definition of a severe thunderstorm would probably focus on electrical activity and the intensity of the rainfall; storms can certainly be severe, by British standards, without large hail or particularly violent local winds. This again underlines the importance of heavy rainfalls research to complement that into hail, lightning and tornadoes. There is definitely much exciting study ahead for TORRO on these inter-related aspects of severe convective storms.

REFERENCES

BROWNING, K. A. (1978): The structure and mechanism of hailstorms. *Meteorological Monographs,* no.38, pp.1-43, American Met. Soc., Boston.

BROWNING, K. A. (1986): Weather radar and frontiers. *Weather, 41,* pp.9-16.

BROWNING, K. and LUDLAM, F. H. (1962): Airflow in convective storms. *Q. J. R. Met. Soc., 88,* pp.117-135.

CLARK, J. E. (1920): The Surrey hailstorm of July 16th 1918. *Q. J. R. Met. Soc., 46,* pp.271-287.

DENT, L. and MONK, G. (1984): Large hail in north-west England on June 7th 1983. *Met. Mag., 113,* 249-264.

ELSOM, D. M. (1985): Tornadoes in Britain: where, when and how often. *J. Meteorology,* vol.10, 100, pp.203-211.

ESSEX FIELD CLUB (1897): The great storm of Midsummer Day 1897. *Essex Naturalist, 10,* pp.112-129.

HARDMAN, M. E. (1968): The Wiltshire hailstorm 13th July 1967. *Weather, 23,* pp.404-414.

HILL, F. F. (1984): The development of hailstorms along the south coast of England on 5th June 1983. *Met. Mag., 113,* pp.345-363.

KEERS, J. F. and WESTCOTT, P. (1976): The Hampstead storm – 14th August 1975. *Weather, 31,* pp.2-10.

LAMB, H. H. (1957): Tornadoes in England 21st May 1950. *Geophysical Memoirs, 12, (99),* London H.M.S.O., pp.1-38.

LUDLAM, F. H. (1961): The hailstorm. *Weather, 16,* pp.152-162.

LUDLAM, F. H. (1980): *Clouds and Storms,* Pennsylvania State University Press.

LUDLAM, F. H. and MACKLIN, W. C. (1959): Some aspects of a severe storm over south-east England, 5th September 1958. *Nubila Verona, 1,* pp.38-50.

MARRIOTT, W. (1894): Thunder and hailstorms over England and the south of Scotland – 8th July 1893. *Q. J. R. Met. Soc., 20,* pp.31-39.

MEADEN, G. T. (1985a): The classification of whirlwind types and their physical origins. *J. Meteorology*, vol.10, 100, pp.194-202.
MEADEN, G. T. (1985b): *A study of tornadoes in Britain.* Prepared for H.M. Nuclear Installations Inspectorate Health and Safety Executive.
MORTIMORE, K. O. and ROWE, M. W. (1984): The hailstorm of 5th June 1983 along the English south coast. *J. Meteorology, 94,* pp.331-336.
NEWSON, A. J. (1977): Heavy thunderstorm at Plynlimon, mid Wales. *J. Meteorology*, vol.2, pp.292-294.
PIKE, W. S. (1987): The Berkshire storm of 10th August 1986. *J. Meteorology*, vol.12, 122, pp.266-269.
PRICHARD, R. J. (1985): Spatial and temporal distribution of British thunderstorms. *J. Meteorology*, vol.10, 100, pp.227-230.
PRICHARD, R. J. (1987): Severe thunderstorms in south-west Essex, 29th July and 22nd August 1987. *J. Meteorology*, vol.12, 124, pp.340-343.
ROWE, M. W. (1985): Britain's greatest tornadoes and tornado outbreaks. *J. Meteorology*, vol.10, 212-220.
SYMONS, G. J. (1879): The thunder and hailstorm of August 2nd-3rd 1879. *Met. Magazine*, May 1879, pp.97-113 and pp.125-128.
WEBB, J. D. C. (1988): Damaging hail in Great Britain and Ireland 1986. *J. Meteorology*, vol.13, 125, pp.18-23 and 100-101.
WEBB, J. D. C. and ELSOM, D. M. (1897): Damaging hail in Great Britain and Ireland 1985. *J. Meteorology*, vol.12, 188, pp.114-121.
WEBB, J. D. C., ELSOM, D. M. and MEADEN, G. T. (1986): The TORRO Intensity Hailstorm Intensity Scale. *J. Meteorology*, vol.11, 114, pp.337-339.

RESPONDING TO THE TORNADO HAZARD IN THE U.S.A. AND THE UNITED KINGDOM AND THE CASE FOR ISSUING TORNADO 'FLASH' MESSAGES IN THE UNITED KINGDOM

By DEREK M. ELSOM
TORRO, Geography Unit, Oxford Polytechic

Abstract: The nature and effectiveness of tornado warnings in the United States is examined and the emergency actions adopted by the public are discussed. The arrangements for issuing severe weather warnings in the United Kingdom are explained and the role of severe weather FLASH messages are highlighted. Though the tornado hazard in the United Kingdom is small in comparison with the United States, it is serious enough – on one or two occasions each year – to warrant the issuing of a tornado alert or FLASH message. Those occasions which pose a threat of property damage, disruption, and injury to a large number of people include (i) large tornado outbreaks, usually associated with a line-squall system (ii) tornadoes forming from a mesocyclone, and (iii) tornadoes associated with severe thunderstorms. For a tornado FLASH message to be issued, reliable confirmation that one area has been already struck by a tornado is needed together with the application of nowcasting (forecasting a few hours ahead). Examples of tornado FLASH messages are described together with advice on what actions the public should take on receipt of the tornado alert.

TORNADO WARNINGS IN THE UNITED STATES

a. The tornado hazard

On average each year, tornadoes kill 300-400 people throughout the world (Thompson, 1982). The United States is the country which contributes most to this total. Between 700-1,100 tornadoes occur each year causing 89 annual deaths on average (1960-86) and a loss variously estimated at 125 million dollars (Burton et al, 1978) through 300 million dollars (Kessler and White, 1983) to 2,000 million dollars (Gordon, 1982). Annual average statistics mask the impact that an individual tornado event can produce. For example, the infamous Tri-State

tornado of 18th March 1925 left a trail of devastation along 350km (219 miles) across Missouri, Illinois and Indiana, killing 689 people, injuring 1,980 people, and leaving over 11,000 homeless. More recently, on 3rd-4th April 1974, an outbreak of 148 tornadoes across 13 states killed 315 people, injured more than 6,000, and caused 600 million dollars worth of damage.

b. Severe Thunderstorm and Tornado Watches

Forecasting the occurrence of severe weather is a key part of weather forecasting in the United States. Not surprisingly, given the relatively higher incidence of violent tornadoes compared with other countries (Elsom and Meaden, 1984), the United States pays particular attention to forecasting the possibility of tornadoes. Synoptic, upper-air, radar and satellite information provide the basis for forecasting when and where tornadoes and/or severe thunderstorms are most likely to occur.

A Severe Thunderstorm Watch is issued when storms are expected to develop to an intensity which may produce large hail and/or damaging winds (58 mph or more) as well as heavy rainfall and lightning. Since all severe thunderstorms are potential tornado producers, a Severe Thunderstorm Watch does not preclude the occurrence of tornadoes. A Tornado Watch means that conditions are favourable for the occurrence of both tornadoes and severe thunderstorms. Severe Thunderstorm and Tornado Watches usually cover an area 225km (140 miles) wide by about 320km (200 miles) long. Such watches have been issued since the 1950's when the National Severe Storms Forecast Center was established at Kansas City, Missouri.

c. Severe Thunderstorm and Tornado Warnings

A Severe Thunderstorm or Tornado Warning is issued when severe weather has already developed and has been reported by spotters or indicated by radar. Warnings are statements of imminent danger and are issued for relatively small areas near and downstream from a severe storm.

Conventional radar and satellite have greatly contributed to providing warnings by their identification of severe storm features. Examples of successful, though not infallible, signature guides include the bow, comma and hook radar echoes as well as bounded weak-echo regions (vaults). For satellites, the overshooting dome/caved-in cloud top and a 'warm hole' in the thunderstorm cloud top are recognised as being related to tornado and downburst occurrence (Fujita, 1979; Wakimoto, 1983). However, such signatures apply to severe thunderstorm complexes or mesocyclones whereas few of the thunderstorms which produce the more common, short-lived and less violent (wind speeds about 100 mph) tornadoes display a tornado-indicator signature on radar or satellites.

Though radar and satellite data are valuable in deciding whether to issue a warning, trained spotters with radio communication provide the most reliable information, especially for tornadoes (PROJECT Skywarn, initiated in 1969, established thousands of volunteer trained spotters). The ability of observers to spot signs of imminent tornado formation (e.g. wall cloud development, cloud base rotation) provides a valuable warning time for communities. The Spotter's ability to be at the right place at the right time has been highlighted by the growing success of tornado intercept or chase teams. Other means of deciding whether a tornado is in the vicinity include the detection of electrical and magnetic emissions (sferics) and listening for distinctive sound effects (variously referred to as sounding like jet aircraft, express trains, or even ten million bees).

THE ROLE OF DOPPLER RADAR IN TORNADO WARNINGS IN THE UNITED STATES

One of the most important developments in recent years in the United States in improving the accuracy of tornado warnings, and the length of the warning time, has been the use of Doppler radar. This type of radar is based on measuring the change in frequency that occurs when a radar signal is scattered by a moving target. The so-called Doppler shift is proportional to the velocity of the target toward or away from the radar. Within a distance of about 225km (140 miles), receivers at radar stations can detect the higher return frequencies from raindrops moving toward the antennas and the lower frequencies of those moving away. High speed computers analyse the contrasting frequencies and translate them into colour patterns on radar image display screens. Increasing degrees of red, for example, would indicate increasing velocities away from the radar, while increasing degrees of green/blue would indicate increasing velocities toward the radar. A tornado is likely to form where the radar screen shows two bright contrasting colours to be in close proximity as this situation indicates a rapidly rotating cloud.

Recognition of this distinctive radar image pattern, signalling the formation of a tornado within the storm system, allows tornado warnings to be issued 20 minutes or more before the potentially dangerous vortex touches the ground. This compares with the two-minute warning provided by conventional radar and weather spotters. The incipient tornado of 24th May 1973, which subsequently devastated Union City, Oklahoma, was detected by Doppler radar 41 minutes before it touched the ground.

The effectiveness of Doppler radar increases dramatically with the number of radar units that can be brought to bear on a given storm. The National Weather Service planned to have a new network of 113 Doppler radar installations operating in the 1990's (called NEXRAD – an acronym for Next Generation Weather Radar) to replace the existing national weather radar system. However, problems of providing funds totalling several hundred million dollars may delay the originally proposed timetable for installation – a decision that may lead to unnecessary loss of life through not having the improved tornado alerts that Doppler radar can provide.

EMERGENCY ACTION FOLLOWING A TORNADO WARNING IN THE UNITED STATES

The purpose of accurately forecasting the occurrence of severe weather is to provide a warning (via radio, television, and community alarm sirens) that gives sufficient time for people to take emergency action and for the emergency services to be placed on stand-by, ready to respond to a disaster. Community officials are expected to produce 'disaster prevention and preparedness plans'. For a warning to be effective, the public and community officials must know what actions to take. This indicates the necessity for public education programmes which create an awareness in the community of what to do when a warning is issued.

Unfortunately, it is almost inevitable that some warnings will fall on deaf ears (Sims and Baumann, 1972).

In the United States, many improvements were made to the efficiency of the tornado watch and warning service in the 1970's. Many more spotters were employed, armed with radios, to alert police and local weather stations when a tornado was spotted. Major technical improvements took place with the use of Doppler radar and improved computer forecast models. The effectiveness of the programme may, in part, be measured by the reduction in deaths caused by tornadoes, even though the population has been rising. Whereas in the 1916-52 period there were, on average, 212 deaths annually attributed to tornadoes, this fell to 119 deaths in the 1953-69 period and 81 deaths in the 1970-86 period. Such figures suggest that the tornado watch and warning system, which began in 1953, halved the number of fatalities caused by tornadoes. However, such statistics conceal that an infrequent tornado event can effect a greater number of deaths in a few minutes than the annual average calculated over a long period.

The United States has undertaken an extensive programme of public education on disaster preparedness in recent years. When a tornado warning is issued the public are advised:

i. take shelter

In those areas of the United States subject to high frequencies of destructive tornadoes, tornado-proof cellars are common place. These are strongly built underground refuges having a stout door flush with the ground. Further, in small communities, the public are made aware that a certain strong community building should provide protection against a tornado. However, the Saragosa experience highlights the limitations of some supposedly strong buildings. On 22nd May 1987 a tornado scythed through the small Texas town of Saragosa (population 185). The wooden-framed homes were completely flattened but most of the townspeople and their children were, by chance, in the sturdily-built community hall. Unfortunately, even this building was not stout enough as the tornado caused the walls to collapse bringing the concrete roof down on those inside. Nearly 40 people were killed and 100 injured.

If tornado-proof cellars are not specifically provided, the advice is to take shelter in basements or in interior small rooms and stairwells. Such rooms are less likely to experience roof and outside wall collapse. Damage surveys have shown that the safest locations are in central rooms or rooms on the opposite side of the house from the approaching tornado, that is, usually the north-east rooms. This finding is in direct contrast to the earlier, and still widely-held idea that the south-west corner is the best place to take cover. However, one reassuring statistic is that even if your house is totally destroyed by a tornado, the chances of you being killed are less than 1% (Eagleman, 1983).

Some locations are more vulnerable than others. With wind speeds in tornadoes increasing with height, residents of high-rise buildings are advised to seek shelter in the basement of the lowest floor possible. Construction sites must surely rank as one of the most dangerous places to be should a tornado strike. Partially-completed buildings are particularly vulnerable to strong turbulent winds, and the number of potentially lethal objects that may be lifted or blown by the wind is enormous. Evacuating a construction site is a priority.

ii. avoid being in a vehicle

There is a natural tendency when confronted by imminent danger to try to escape from an area. Unfortunately, at night or in the darkness of the storm it is difficult to know in which direction to head to be safe – a storm may generate several tornadoes in an area. Many people have been killed in their cars, as they tried to flee, by being overtaken by a tornado, e.g. accounting for over half the deaths in the Witchita Falls tornado of 1979. Trees and telegraph (utility) poles brought down by a storm (due to the tornado or to associated downbursts and squalls) can crash vehicles, while flying debris – corrugated iron sheets and sheets of wood – make lethal missiles for any car occupant. Further, panic can lead to increased likelihood of a motor accident. It is much safer to stay put and take shelter in a strong, preferably a basement, room.

iii. stay away from windows

Sometimes official advice can increase the likelihood of being injured by a tornado. At one time it was believed that the rapid atmospheric pressure change associated with tornadoes caused the roof, and sometimes the walls, of a house to 'explode'. It was thought that opening the windows or doors of the house would ensure that air pressure equalised more readily and so not exert such explosive forces on the building. However, people following such advice often received injuries from flying glass and other debris.

It is now accepted that the pressure change is not so important in causing roofs to lift or walls to buckle outwards and collapse. Rather it is the buoyancy or suction force that strong winds exert on a rooftop (regardless of differences between internal and external pressures within the building) that cause the damage. Further, wind entering a building, through an open window (deliberately opened or broken by flying debris) exerts a ram-pressure effect which may lift a roof or push the walls outwards. Opening a window therefore makes little difference except to increase the possibility of the ram-pressure effect operating and to increase the likelihood that the person opening the window, at the approach of a tornado, will be hurt by flying debris. The advice nowadays is to take cover as quickly as possible.

iv. evacuate mobile-homes

Mobile homes are particularly vulnerable to strong winds (exceeding about 60 mph) because they have relatively large surface area to weight ratios. In the United States, over 100,000 mobile homes, representing two per cent of the national total, are damaged each year by windstorms (to the extent that insurance claims are filed). Many deaths and injuries to occupants are due to strong winds and/or tornadoes lifting, toppling, rolling, and even crushing mobile homes. The American Meteorological Society (1985) issued a warning that greater attention should be given to securing such structures and that mobile-home parks should provide a strong building as a storm shelter in which mobile-home occupants may seek temporary shelter. Even if mobile homes are tied down they should be evacuated following a severe storm warning because their thin walls make them extremely vulnerable to windborne debris.

v. minimise windborne debris

Most tornado deaths and injuries result from flying debris. The rotating core of the tornado tends to accumulate airborne debris in the form of roofing tiles, tree

branches, pieces of wood, shards of glass, gravel and pieces of sheet cladding. This debris poses a threat to people and causes extensive secondary damage to glazing, doors, roofs, cladding and vehicles which in turn generates more debris.

Protection of life is the priority during a Tornado Warning but, if time allows, any objects that could be readily lifted or blown away by the strong winds (e.g. dustbins, planks, garden furniture) can be moved indoors or secured firmly. Window shutters can be secured. Again, if time allows, vehicles can be moved away from trees, poles and lamp-posts which may be toppled during the storm. Driving a vehicle into a garage ensures that it will not be damaged by flying or falling debris (though flat-roof garages can often be damaged more than other parts of a building).

SEVERE WEATHER WARNINGS IN THE UNITED KINGDOM

a. Severe weather forecasts and FLASH messages

Forecasting severe weather is an important service provided by the Meteorological Office. If severe weather is forecasted, a warning is issued through the Weather Centres, and it is featured in the weather forecasts regularly provided by television, radio and telephone. Recent examples include snow warnings issued on the evening of 22nd January 1988, and the warning of strong winds expected to cause damage to property on 9th February 1988.

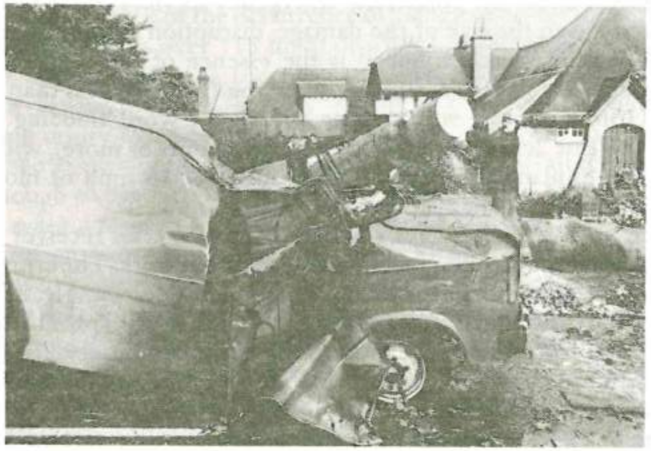


Fig.1: One of the numerous damage incidents caused by an outbreak of 31 tornadoes across southern England on 20th October 1981 *(Surrey Daily Advertiser)*. Surely communities should receive a warning of such events?

Some organisations or specialist users pay to receive directly warnings of particular severe weather types. Thus, the Water Authorities want to be warned of heavy rainfall; the London Fire brigade of winds expected to exceed more than 30 mph (because of the difficulty of using long ladders); British Rail to be warned of gales (because of problems with overhead lines); the Central Electricity Generating Board to be warned of thunderstorms (because of disruption to electricity supplies by lightning) and Local Authorities, police and motoring organisations to be warned of snow, icy roads, heavy rain and fog. Such warnings may be issued many hours or several days in advance and be regularly updated.

In addition to routine severe weather forecasts, the Meteorological Office (via the Weather Centres, especially London Weather Centre) issues 'FLASH' messages. These are urgent severe weather warnings alerting the public of the 'occurrence of severe weather which may cause considerable inconvenience to a large number of people and/or present a danger to life' (Meteorological Office, 1988). They are only issued when there is a virtual certainty of severe weather in an area, being usually based on actual observations. The Meteorological Office criterion is that FLASH messages refer to 'severe weather conditions which are actually occurring or are confidently expected to commence within three hours' (Met. Office, 1988).

Severe weather FLASHES may be regional or national and they are sufficiently urgent to justify interrupting radio and television programmes as well as being sent to the emergency services and some specialist users. A recent example of a FLASH message was that issued at 0120 GMT, a few hours before the worst of the gales struck England and Wales, on 16th October 1987. As many as 30-40 FLASH messages may be issued each year although this total includes several repeats or updates given during a severe weather spell. Some messages may be limited to one region (associated with the 18 major urban areas) while some may be national. FLASH messages allow the public, the emergency services and specialist users to take actions to lessen the risk of the damage, disruption and injury (even death) posed by the severe weather. Speed is the essence of the scheme. Currently, FLASH messages are issued in cases of dense fog (visibility less than 50 metres), heavy rains (15mm or more within three hours – the word 'flooding' is avoided), heavy snow (at least 2cm per hour lasting for two hours or more), widespread icy roads, and severe inland gales (mean wind speed of 46 mph or more, or gusts exceeding 69 mph) and blizzards/severe drifting snow.

In addition to FLASH messages, the BBC Motoring Unit receives warnings of hazardous weather for broadcast on the BBC radio network. The criteria for these messages are less severe than for FLASH messages. For example, in the case of strong winds, the threshold is a mean speed greater than 35 mph. Further, because of a possible call for military aid to help the civil community, the Ministry of Defence requires to be warned when wind speeds of 50 mph or more may occur over inhabited parts of the U.K.

A warning or FLASH message concerning tornadoes has never been issued in the United Kingdom. On a few occasions a tornado, which had struck an hour or two earlier, has been mentioned during a regular television weather forecast to illustrate the severity of thunderstorms occurring in an area. However, its mention has been for interest or 'novelty value' rather than suggesting that other communities in the area may experience a tornado.

b. Is the British tornado hazard serious enough to justify a severe weather warning?

A comparison of tornado statistics for the United States and the United Kingdom reveals a striking contrast in the threat posed by their respective tornado hazard. Whereas tornadoes may cause nearly 100 deaths each year in the United States, it is rare for a tornado in the United Kingdom to lead to loss of life – though serious injuries occur.

Tornado statistics reveal that severe or strong tornadoes, capable of destroying a mobile home or removing an entire roof off certain houses (intensity T4 or F2 – with winds exceeding 115 mph), represent 9% of all known tornadoes in Britain (1950-84 period – Meaden, 1985) whereas they account for 35% in the United States (1950-83 period – Kelly and Schaefer, 1983). Further, although the U.K. has yet to document a tornado in the 'violent' category (intensity of TORRO force T8-T10 or F4-F5 – with winds exceeding 200 mph) this century (though nearby northern France and Belgium have experienced such devastating tornadoes in recent years), the United States has experienced about 400 in the past 35 years. Although only two per cent of all documented tornadoes in the United States are in this violent category they are 'killer tornadoes', being responsible for 68% of the total number of deaths (Schaefer et al, 1980).

In general, the tornadoes that occur in Britain – on as many as 31 days each year – are what the Americans term 'weak' or 'mini' tornadoes. About two-thirds of all British tornadoes are in this category (T0-T2 or F0-F1), with wind speeds typically between 42-92 mph. Such short-lived tornadoes, may remove roof tiles and topple tall chimney stacks of some buildings, blow down fences, damage sheds and garages, and topple some trees along a short track, usually less than a few kilometres. To warn of a *single* such 'mini' tornado could not be justified, even if such an event could be forecast, which is itself unlikely. However, if there was a high degree of confidence of the occurrence of a single long-lasting severe tornado (T4 or more, with winds over 115 mph) or a large outbreak (say, 10 or more) of tornadoes of varying intensity, then this is a different matter. Such a situation constitutes a severe weather hazard, posing a threat of property damage, disruption and injury to a large number of people. Such occasions may number only one or two a year – perhaps none at all in certain years – but the tornado threat is serious enough to warrant the issuing of a warning (Fig.1).

c. Occasions when a tornado FLASH message should be issued.

The distinction between issuing a tornado FLASH message and a tornado forecast needs to be reiterated. Issuing a tornado FLASH message would depend upon knowing that a tornado has actually formed in one area. The decision to issue a FLASH message would be based on the confident expectation that one or more tornadoes may continue to strike in that area or in some other specified area. Such a tornado alert would not extend further than a few hours ahead. In contrast, a tornado forecast would warn of the possibility of one or more tornadoes being expected in a region (comparable with the U.S. Tornado Watch) and would be issued before a tornado has occurred. It might be issued six hours or even more in advance of the possible tornado. However, until appropriate forecast models for British tornadoes have been developed and tested, such forecasts will not be available – if at all. Thus in the near future at least, any tornado 'warning' would be limited to a tornado FLASH message.

Issuing a tornado FLASH message would require reliable confirmation that an area had been struck by a tornado. Once this information had been received, 'nowcasting' could be applied. Nowcasting refers to weather forecasting, largely based on predicting the movement and development of weather systems (that are already being tracked) over a period up to about six hours. Radar and satellite provide the key meteorological information for this system. The Meteorological Office have identified 'nowcasting' as a growth area and considerable funds have been allocated to develop a national radar network which provides information that can be intergrated with Meteosat data (known as the FRONTIERS project). This system measures rainfall intensities over 5km x 5km areas and is able to track the movement of isolated or frontal storms. Providing that the storm's movement is not erratic, an excellent extrapolation (nowcast) is possible.

Fig.2: The tornado which swept through Bicester, Oxfordshire, on 21st September 1982, left an almost straight 1.2km long by up to 100m-wide track of damage *(Oxford Mail and Times)*. Within three hours of it forming, 22 other tornadoes occurred in southern and eastern England along a well-defined cold front. The position of the front could be readily tracked using radar of the FRONTIER system.

Confirmation that a tornado has struck an area would require good communication links with the police, fire, or other emergency services which quickly reach an area that has suffered damage by a tornado. A cursory glance at the narrow path of damage, the nature of the damage, together with eyewitness reports, may be sufficient for confirmation (Fig.2). Even so, there could be occasions when mistakes are made, such as the damage having been caused by a downburst or microburst (thunderstorm outflow winds) rather than a tornado.

Following confirmation that one or more tornadoes have occurred, there are three occasions for which a tornado FLASH message may be issued:

(i) A LARGE TORNADO OUTBREAK. If many tornadoes are associated with a line-squall system and the system is expected to continue producing tornadoes, then a tornado FLASH message should be issued. Examples: On 23rd November 1981, 105 short-lived tornadoes caused structural damage across the

country. These tornadoes were typically of force T2 but two reached T4 and one at Holyhead reached force T5 (Meaden and Rowe, 1985; Rowe and Meaden, 1985). The tornadoes, associated with a non-thundery cold front, first struck at 1034 GMT in Wales and the north-west of England. A succession of tornadoes then occurred across England along a 200km long section of the cold front. The Midlands experienced tornadoes around lunchtime and the last tornado formed in East Anglia and south-east Essex at 1545 GMT. Other recent large tornado outbreaks associated with fast-moving fronts include 20th October 1981 (31 tornadoes), 21st September 1982 (23) and 8th February 1984 (21). Tornado activity on these occasions lasted 3-5 hours (Elsom, 1983; Elsom, 1985; Turner et al, 1986).

(ii) A TORNADO CYCLONE. If one or more tornadoes are associated with a mesocyclone or tornado cyclone – the type of situation which gives rise to severe tornadoes in the United States – then a tornado FLASH message should be issued. Tornadoes associated with such systems have the potential to be particularly severe and long-lasting, though they occur only infrequently. Example: At 0830 BST on 24th June 1979, a tornado, associated with a 60km-diameter mesocyclone, struck Windsor. Within a few hours, several other locations north-north-east of Windsor suffered tornado damage (Buller, 1979; Grant, 1980; Heighes, 1979). Though this occasion did not produce particularly strong tornadoes (force T2/3), it is cited as an example because the author received notice (via the police) that a tornado had caused structural damage in Windsor, and that it was moving northwards, within an hour of it striking. The potential for warning other communities in the general direction of travel of the parent storm was thus highlighted.

(iii) A SEVERE THUNDERSTORM OUTBREAK WITH TORNADOES. If one or more short-lived tornadoes are associated with other severe thunderstorm weather situations e.g. exceptionally heavy rainfall, large hail (exceeding 16mm diameter or marble size), and strong blustery winds (squalls, downbursts), then a FLASH message should be issued. Example: During the night of 20th/21st November 1986, severe thunderstorms occurred in a 200km-wide band extending from south-west Wales to the eastern English Channel (Waters, 1987). Four tornadoes (or tornado-waterspouts) formed, causing structural damage to 300-400 houses at Swindon, Wiltshire, at 2230 GMT; at Selsey, West Sussex, at 0039 GMT; and at Lewes and Portslade-by-Sea in East Sussex around 0130 GMT (Elsom and Rowe, 1988). At Selsey, the damage was so severe that 300 residents were evacuated for the rest of the night while damaged houses were made safe. (Matthews 1988, Elsom and Rowe 1988).

Clearly, all the above situations are ones that allow for the weather system producing tornadoes to be tracked using the FRONTIERS system. The movement of the systems over several hours could be forecast/extrapolated with some confidence.

d. The reaction of the British public

Given that British tornadoes seldom reach the intensity of the worst American tornadoes, there is some concern in even mentioning the word 'tornado'. To some of the public, the mention of a tornado produces the image of Dorothy's experience in *The Wizard of Oz* as she watched a dark twisting tornado coming towards her across the plains of Kansas. Further, the public's image of the damage caused by a tornado may be the almost total community devastation shown in occasional television reports from the United States. Clearly, at present, there is concern that warning of a tornado in Britain may cause excessive alarm amongst the public.

If tornadoes are to be specifically mentioned in a FLASH message, then the Meteorological Office and TORRO have a role to play in educating the public to realise that the structural damage usually caused by British tornadoes is similar in severity to that caused by gales or severe gales, though more limited in the total area affected. It is vital that this image of British tornadoes is conveyed to the public *before* becoming committed to the issuing of tornado FLASH messages. The issuing of a FLASH message is intended to increase community preparedness. It is *not* intended to cause excessive fright amongst the public and nor is it intended to provide the opportunity for the media to over-sensationalise the occurrence of severe weather.

Supplementing any tornado FLASH message must be clear advice as to what actions the public and the emergency services should take.

e. The format of FLASH messages

FLASH messages are written to have maximum impact, and all messages begin with the preamble:

'Here is a FLASH message of severe weather in (area affected).'

The body of the text then indicates the type of weather causing concern, the period it is expected to last and the area affected. Reference to actual weather reports and to the type of inconvenience or danger envisaged may be emphasised. For example, in the case of severe gales the text indicates the maximum gust speed likely to occur (in miles per hour) and includes the phrase "some structural damage may occur". An example, omitting the preamble, for severe gales is:

'Winds are expected to increase to severe gale force in the Edinburgh area within the next hour or so and will remain at this level until this evening. Gusts up to 70 or 80 mph are likely and some structural damage may occur.' (Meteorological Office, 1988).

The FLASH message issued at 0120 GMT on 16th October 1987, read:

'Severe Weather Flash. Here is a FLASH message of severe weather in England and Wales. Severe gale force winds already affecting southern districts will spread northwards across many parts of England and Wales before morning. Gusts in excess of 70 mph are expected and some structural damage may occur.'

f. Tornado FLASH messages

Examples of the form that tornado FLASH messages might take are given below. These illustrate the three types of severe weather situations referred to earlier which may justify the issuing of such a warning.

Example 1 (issued at 1115 GMT on 23/11/81 by Birmingham Airport):

'Several tornadoes have been reported from North Wales, Merseyside and Greater Manchester along a cold front moving south-eastwards across the country. Short-lived tornadoes, with gusts up to 80 or 90 mph, are expected in the West Midlands in the next hour or two. Some structural damage may occur.'

Example 2 (issued at 1015 BST on 24/6/79) by London Weather Centre):

'The tornado which struck Windsor at 0930 BST, causing some structural damage, is expected to affect other parts of Berkshire and parts of Hertfordshire shortly. Winds gusting in excess of 90 mph are likely and some structural damage may occur. You are advised to remain indoors during the next two hours.'

Example 3 (issued at 0015 GMT on 21/11/86 by Southampton Weather Centre):

'The severe thunderstorms, which earlier produced heavy rain, large hail and a tornado in Wiltshire, are expected to affect parts of Hampshire and Sussex in the next hour or two. Driving conditions will become hazardous. Gusts up to 80 or 90 mph are likely in some localised areas and some structural damage may occur.'

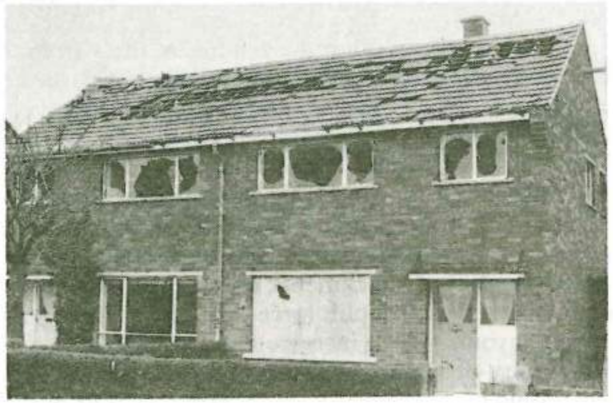


Fig.3: More than 130 homes were damaged and three people injured by a tornado at Doncaster on 14th January 1984 *(Sheffield Newspapers)*. Damage to this house highlights the importance of staying away from windows.

In addition to the severe weather FLASH message, radio and television may include further information on the severe weather following interviews with staff from the appropriate Weather Centre (or London Weather Centre since it coordinates all FLASH messages).

g. advice to the public on action to take following receipt of a tornado FLASH message.

It is important that the public, as well as emergency services and specialist users, know what actions they should take following receipt of a tornado FLASH message. The principal threat to the public by tornadoes is the very strong winds, which like severe gales, may cause some structural damage. Hazardous road conditions may also be a problem because of falling trees and broken branches strewn on roads.

An example of the advice statement that could be issued, which is similar to that issued for severe gales, is:

- secure anything liable to blow away (dustbins, planks, garden furniture) or move such objects indoors;
- stay indoors if you can and stay away from the windows (Fig.3);
- bring pets indoors;

* do not park cars under trees, telegraph poles or lamp-posts (move cars into garage if time allows);
* do not make a journey unless you have to;
* if you have to travel, drivers should take extra care (look out for fallen trees or branches on roads);
* know where water, gas and electricity supplies can be switched off;
* contact elderly or disabled neighbours to check on their safety before and after the storm;
* temporarily evacuate caravans/mobile homes for the security of a stronger building.

LONG-TERM RESPONSES TO THE TORNADO HAZARD IN THE UNITED KINGDOM

In terms of preventing serious injury – even loss of life – from tornadoes, it is important that accurate severe weather FLASH messages are issued, together with advice on what actions to take. However, there are other effective responses that can be made to the British tornado hazard.

To reduce tornado damage to buildings, as well as to reduce injuries to their occupants, various long-term adjustments may be undertaken and these are similar to those advised for gales. Improvements in the design of buildings can be made (e.g. avoid unnecessary overhanging structures such as porches; ensure the use of nonlift roofs with reinforced attachments; use steep-angle roofs rather than flat or low-angle roofs so as lessen the uplift force – the airfoil effect – imposed on the roof; avoid building layouts which increase wind channelling). Given the large costs to the community of wind damage, economic incentives to builders and property owners should be considered such as offering grants or lower insurance rates. Of course, adequate property insurance cover itself is an appropriate way for property owners to minimise the cost of damage.

It is clear from the nature of some structural damage due to tornadoes (and gales) that more care needs to be taken in the construction stage of buildings (e.g. better tying of the inner and outer brick walls of house gable ends so that the suction force of the wind is less likely to remove the outer skin – Cook, 1984). Better house maintenance needs to be carried out (toppling of brick chimney stacks by wind is often due to deterioration; roof tiles and slates are lifted because they have become loose; ridge tiles are removed because of mortar deterioration). Improvements to older properties can be undertaken to reduce their vulnerability to strong winds (e.g. take down high slender chimney stacks and pots if no longer needed as they are likely to topple and may cause additional damage if they fall through the roof – Fig.4; install attic vents on the downwind side to help equalise pressures above and below the roof during strong winds). Static caravans should be anchored securely to a concrete base and prefabricated homes and classrooms can be made stronger.

Obviously, major structures (e.g. nuclear power stations, suspension bridges) need to be designed to be safe in the most exceptional winds. When such a structure is to be designed to withstand the most extreme winds, it is important that the tornado risk is adequately assessed (International Atomic Energy Agency, 1981; Meaden, 1985).

Fig.4: Tall chimneys are vulnerable to strong winds – even these large chimneys, weighing 1.5 tonnes each. They were toppled by a tornado at Teignmouth on 26th January 1984 *(West of England Newspapers).* Removal of redundant chimneys reduces the potential damage to buildings.

CONCLUSIONS

Tornado warnings and tornado hazard education have resulted in the saving of 100 lives a year and a considerable reduction in injuries in the United States. The threat of loss of life and serious injury from tornadoes is small in the United Kingdom in comparison with the United States. However, there are one or two occasions each year in Britain when tornadoes do pose a threat of sufficient seriousness to justify the issuing of a tornado FLASH message. At these times, tornadoes threaten property damage, disruption and injury to a large number of people. Issuing tornado FLASH messages on such occasions would reduce the risk of injury. Property damage by tornadoes, together with resulting injuries to occupants, could be reduced by adopting the advice accompanying these 'tornado warnings'. In the long-term, an increased awareness of the British tornado hazard would direct more attention to the design, construction and maintenance of structures that would reduce property susceptibility not only to tornadoes but to severe gales too.

Note: Wind speeds are given in miles per hour in this article as these are the units currently employed in severe weather FLASH messages.

REFERENCES

AMERICAN METEOROLOGICAL SOCIETY (1985): Mobile homes and severe windstorms. *Bull. Amer. Met. Soc., 66,* 857.
BULLER, P. S. J. (1979): Tornado damage in the Home Counties, 24th June 1979. *J. Meteorology, 4,* 235-240.
BURTON, I., KATES, R. W. and WHITE, G. F. (1978): *The Environment as Hazard.* Oxford Univ. Press: New York.
COOK, N. J. (1984): Performance of buildings in the United Kingdom. *Eng. Struct., 6,* 248-255.
EAGLEMAN, J. R. (1983): *Severe and Unusual Weather.* Van Nostrand Reinold: New York.

ELSOM, D. M. (1983): Tornado at Bicester, Oxfordshire, on 21st September 1982. *J. Meteorology, 8,* 141-148.
ELSOM, D. M. (1985): Tornadoes in association with a cold front: the example of the outbreak of 21 tornadoes on 8th February 1984. *J. Meteorology, 10,* 4-15.
ELSOM, D. M. and MEADEN, G. T. (1984): Spatial and temporal distributions of tornadoes in the United Kingdom 1960-1982. *Weather, 39,* 317-323.
ELSOM, D. M. and ROWE, M. R. (1988): Tornado causes emergency evacuation at Selsey, southern England, during the night of 20th-21st November 1986. *J. Meteorology, 13,* to be published.
FUJITA, T. T. (1979): Objectives, operation, and results of Project Nimrod. *Preprints of 11th Conference on Severe Local Storms, Kansas City, Missouri.* American Met. Society: Boston, pp.259-266.
GORDON, P. (1982): *Special Statistical Summary: Deaths, Injuries and Property Loss by Type of Disaster, 1970-1980.* U.S. Federal Emergency Management Agency, Washington, D.C.
GRANT, K. (1980): Mesoscale surface humidity observations near the Home Counties tornado, 24th June 1979. *Met. Mag., 109,* 259-267.
HEIGHES, J. M. (1979): The tornado-cyclone of 24th June 1979 over southern England. *J. Meteorology, 4,* 233-235.
INTERNATIONAL ATOMIC ENERGY AGENCY (1981): *Extreme Meteorological Events in Nuclear Power Plant Siting, Excluding Tropical Cyclones.* Safety Series No.50-SG-S11A, IAEA: Vienna.
KELLY, D. L. and SCHAEFER, J. T. (1983): A minimum assumption tornado risk model. *Preprints of 13th Conference on Severe Local Storms, Tulsa, Oklahoma.* American Met. Society: Boston, pp.128-131.
KESSLER, E. and WHITE, G. F. (1983): The thunderstorm in human affairs. In *Thunderstorms: A Social, Scientific and Technological Documentary,* E. Kessler (ed.), Univ. Oklahoma Press, Norman, pp.3-18.
MATTHEWS, P. (1988): The Selsey tornado, *J. Meteorology, 10,* to be published.
MEADEN, G. T. (1985): *A Study of Tornadoes in Britain with Assessments of the General Tornado Risk Potential and the Specific Risk Potential at Particular Regional Sites.* Report prepared for H.M. Nuclear Installations Inspectorate Health and Safety Executive. TORRO: Bradford-on-Avon.
MEADEN, G. T. and ROWE, M. W. (1985): The great tornado outbreak of 23rd November 1981 in which North Wales, central and Eastern England had 105 known tornadoes in about five hours. *J. Meteorology, 10,* 295-300.
METEOROLOGICAL OFFICE (1988): *The Storm of 15th/16th October 1987.* Met. Office: Bracknell.
ROWE, M. W. and MEADEN, G. T. (1985): Britain's greatest tornado outbreak. *Weather, 40,* 230-235.
SCHAEFER, J. T. et al (1980): Tornadoes: when, where and how often. *Weatherwise, 33,* 52-59.
SIMS, J. H. and BAUMANN, D. D. (1972): The tornado threat: coping styles of the north and south. *Science, 176,* 1386-1391.
THOMPSON, S. A. (1982): *Trends and Developments in Global Natural Disasters, 1947 to 1981.* Natural Hazard Research Working Paper 45, Univ. of Colorado, Boulder.
TURNER, S., ELSOM, D. M. and MEADEN, G. T. (1986): Outbreak of 31 tornadoes associated with a cold front in Southern England on 20th October 1981. *J. Meteorology, 11,* 37-50.
WAKIMOTO, R. M. (1983): The West Bend, Wisconsin storm of 4th April 1981: a problem of operational meteorology. *J. Climate and Applied Meteorology, 22,* 181-189.
WATERS, A. J. (1987): Meteosat and radar rainfall imagery interpretation on the night of 20th/21st November 1986. *Met. Mag., 116,* 87-91.

A SURVEY OF BALL LIGHTNING

By MARK STENHOFF
Director, TORRO Ball Lightning Division
and
Head of Physics, St. Dunstan's College, London SE6 4TY

Abstract: A study of about 200 first-hand accounts of observations of alleged ball lightning indicates that about 80% may be readily explained by other means, and that the residual reports may mostly be called into question because of the time elapsed between event and report. The validity of earlier statistical studies is thus called into question. The low signal-to-noise ratio may be responsible for the absence of a single, convincing theory of ball lightning. More promising means of establishing the existence and nature of ball lightning are offered by techniques of instrumented observation, but these techniques cannot be dedicated to the study of ball lightning alone.

INTRODUCTION

"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."

James Dale Barry[1]

Ball lightning is alleged by some to be a rare atmospheric phenomenon usually associated with thunderstorms, while others hold that it does not exist. This controversy has continued for centuries. Twelve years ago, I published a report of a ball lightning event[2] which generated a good deal of publicity, and which resulted in my receiving a large number of first-hand accounts of alleged ball lightning. As a result of this, I decided to conduct a detailed study of eyewitness accounts of alleged ball lightning, in the Department of Physics at Royal Holloway College, University of London. This study has taken six years, and its aim was a critical evaluation of the evidence for the existence of ball lightning. The publication of this survey in 1988 marks the 150th anniversary of the publication of the first review and survey of ball lightning, written by François Arago[3].

I embarked on my study with an open mind on the question of the existence of ball lightning, although many of the accounts I had received seemed both plausible and difficult to explain by other means. I had also read a number of very convincing first-hand accounts in journals such as *Nature* and the *Journal of Meteorology.* My original plan was to conduct a literature search of ball lightning reports, but I soon encountered difficulties in using these as a source of further study. The information content of reports was not standardised, most were written on the assumption that ball lightning was their cause, and most were paraphrased accounts by scientists. I therefore decided to enlarge my own collection of first-hand accounts, and obtained further reports by appeals in the *New Scientist* and *Physics Bulletin.* I was also provided with collections of reports by Michael Rowe of TORRO and by Professor Sir Brian Pippard, who received a number of reports now stored in the Library of the Royal Society.

THE STUDY OF BALL LIGHTNING

Natural phenomena fall into four categories: (i) those which may be reproduced in the laboratory, perhaps in a scaled-down form, and subjected to direct experimental study, e.g. water waves in a wave-tank; (ii) those which, although remote and not reproducible under laboratory conditions, are ever-present and may receive remote experimental study, e.g. stars and planets; (iii) transient but predictable phenomena, where remote sensing and measuring devices may be set up when the phenomenon is expected, e.g. tornadoes, eclipses; and (iv) transient and unpredictable phenomena, which may not be adequately reproduced in the laboratory.

There are considerable difficulties in studying those phenomena in category (iv). If ball lightning exists, it would seem to be such a phenomenon. Historically, acceptance by scientists of the reality of such phenomena tends to be reluctant (e.g. the reaction of the French Academy of Sciences to reports of 'stones falling from the sky'[4]).

When I embarked on my research I found myself in the curious position of attempting to study a phenomenon whose very existence is in question, with the evidence for its existence being based almost exclusively on the testimony of eyewitnesses. Although this state of affairs might be regarded as less than satisfactory, the fact remains that phenomena exist which are both rare and unpredictable which, in the early stages of investigation, may only be studied in this way.

In order to attempt an interpretation of the experiences eyewitnesses claim to have had, and thus to isolate physical factors from psychological effects, I found it necessary to acquire a working knowledge of the psychology of perception, as well as of natural and artificial phenomena which might be misidentified as ball lightning. Other phenomena which might be mistaken for ball lightning were subjected to a very thorough study, and the means by which such misidentifications could be recognised were established.

The physical properties of random, unrepeatable phenomena may also sometimes be deduced from any physical traces remaining after an event. (Historically, this was the method by which the nature of meteorites was established by Chladni[4]). In most reports of ball lightning, I found that physical traces may be explained as the effects of conventional linear lightning, as indicated below. Most photographs of alleged ball lightning may similarly be otherwise explained.[1]

PREVIOUS STUDIES OF BALL LIGHTNING REPORTS

Because of the way in which ball lightning is reported, a 'folklore' has developed around the subject of ball lightning, the common description of the characteristics of ball lightning being based partly on individual reports and partly on statistical surveys. Too much reliance has been placed on individual reports, and the statistical surveys[5] have mostly accepted as ball lightning any phenomenon so described by the observer and hence have a very low signal-to-noise ratio, (which according to the present study, is no better than 16%, as indicated below).

MISPERCEPTION AND MISIDENTIFICATION

A discussion of psychological and perceptual aspects indicated that descriptions could not always be taken at face value, and that many accounts of alleged ball lightning would be expected to contain substantial inaccuracies. Previous studies of other phenomena[6] suggest that about 50% of reports prepared more than 24 hours after an unusual event contain substantial errors, with the percentage increasing to 75 after three days and 90 after four days.

EVALUATION OF BALL LIGHTNING REPORTS

There is evidently a direct association between thunderstorm activity and most ball lightning reports, and a less reliable relationship between alleged ball lightning formation and conventional linear lightning. Many of the effects attributable to ball lightning may easily be explained as those of conventional linear lightning, for example thermal effects, damage to aircraft, puncturing of dielectrics such as glass, damage to trees, mechanical damage and shock-wave damage, effects on the human body, etc. Side-flashes may be responsible for electrical damage by conventional linear lightning being transmitted over large distances or carried into buildings. In only very few cases of damage attributed to ball lightning could the damage not be explained as caused by ordinary lightning.

Popular confusion about the nature of ordinary lightning, and the concepts of 'thunderbolts' which is still prevalent, can lead to misidentification of ordinary lightning flashes as ball lightning. Many ball lightning reports have their cause in St. Elmo's fire, a commonplace form of coronal point discharge. A wide range of other phenomena may give rise to reports of ball lightning, although only a small proportion of these would necessarily be associated with thunderstorms. A few ball lightning reports may be explained by positive after-images.

DOES BALL LIGHTNING EXIST?

In the present survey, approximately 200 reports of ball lightning were subjected to a well-defined evaluation procedure to determine whether they could receive simpler explanations. Only 111 contained sufficient information for evaluation. Of these, almost 80% of the reports could plausibly be thus explained, demonstrating the invalidity of previous statistical studies of ball lightning which accepted as ball lightning any event so described by the observer. Of the 16 unexplained reports, only one was written within 24 hours of the alleged event, and many of the other accounts were prepared after a delay of several decades, during which time the anecdotes had doubtless been retold and inadvertently embellished many times. Scientific evidence for the existence of ball lightning is thus very weak, but this may in part be due to the manner in which it is reported.

Continued routine study of ordinary eyewitness accounts is unlikely to yield further useful information. It was found that the majority of reports of alleged ball lightning could be explained by other means, and there was only a very small residue of reports which could not easily be thus explained. A large proportion of the reports (23%) could be attributed to corona discharge effects such as St. Elmo's fire, or by familiar effects of conventional linear lightning (10%). The validity of many previously published statistical studies of ball lightning was thus shown to be doubtful.

Possible observations of ball lightning have occasionally been made by automated instrumentation, for example, by the Prairie Network meteor observing stations[7] and also in the course of studies of ordinary lightning[8], and triggered lightning experiments have produced phenomena resembling ball lightning[9]. These methods of study offer far more hope for productive investigation than continued studies of eyewitness descriptions.

BALL LIGHTNING MODELS AND EXPERIMENTS RELATING TO BALL LIGHTNING

Very few hypotheses concerning the nature of ball lightning have evolved to the status of physical models. Since ball lightning reports show a strong correlation with thunderstorm activity, ball lightning models should necessarily take into account the special atmospheric and physical conditions associated with thunderstorms. Some aspects of descriptions of ball lightning, such as time of incidence within a storm, or geographical or temporal relationship to ordinary lightning, may profitably provide useful information concerning its mode of formation. There are several different types of conventional linear lightning, and it may be that one of these in particular, for example 'hot lightning', could alone generate ball lightning phenomena.

Discharge models of ball lightning (such as the Finkelstein-Rubenstein and Powell-Finkelstein models[10]) have the advantage of relative simplicity and association with familiar phenomena, such as St. Elmo's fire, and the availability of an abundant source of energy, i.e. that of the thundercloud itself. In general, their limitation is an accounting for disembodied and evidently independent regions of luminosity. Without modification or extension, they do not readily explain the formation of ball lightning inside 'Faraday cage' type enclosures such as metallic aircraft fuselages, although few such enclosures are perfect Faraday cages. However, the Powell-Finkelstein model makes reasonable attempts to overcome these difficulties. Discharge models which depend on combustion of low concentrations of natural methane, such as those discussed by Barry, may offer a better description of *ignis fatuus* than of ball lightning.

Plasmoid models[11] are usually based on formation of a vortex ring from the lightning channel by a plasma instability in the lightning column (such as the 'pinch' or 'kink' instabilities), by the misalignment of two oppositely-directed conduction channels, or by thermal ablation. These models could only account for ball lightning formed in the immediate vicinity of a lightning channel, and describe phenomena which would be expected to have high translational velocities and to exhibit significant convection effects because of their high temperature. Ball lightning thus formed would also be expected to be associated with substantial magnetic fields. A further major difficulty is in explaining how such plasmoids, which would be expected to be subject to instabilities, could be magnetically self-confined for several seconds (as is claimed for ball lightning); although experimentally produced plasmoids have lifetimes which are evidently extended through magnetic self-containment, these lifetimes fall short of those described in ball lightning reports by at least one order of magnitude.

Chemical models[12] of ball lightning are based on reactions between products of the lightning discharge (such as ozone or oxides of nitrogen). Exothermic chemical reactions, however, would be expected to produce thermally convecting volumes of gas, and do not adequately account for the stability of shape and size described in ball lightning. In common with the plasmoid theories, the chemical models only account for ball lightning formed close to a lightning channel.

Neither the plasmoid nor the chemical models could easily explain the formation of ball lightning within enclosures, although the ablation theories of plasmoid formation would enable ball lightning to form through small perforations in a surface struck by ordinary lightning.

Nuclear models[13] of ball lightning, including those describing micrometeorites of antimatter[14], predict that ball lightning would be radioactive. This is not supported by eyewitness descriptions of ball lightning reportedly seen at short range.

Kapitsa's model[15], based on natural radiofrequency radiation from lightning, fails to receive general support from intensity measurements of radiation from lightning in the gigahertz waveband required by the model[16], although some measurements have been offered in its support[17]. The most energetic forms of lightning, such as 'lightning superbolts'[18] or 'positive giants'[19] may produce significantly stronger radio emissions.

One investigator[20] concluded that, if external sources of energy were eliminated, only chemical theories could account for the extended luminosity of ball lightning. Another[15] used a scaling argument, based on data from fireballs from nuclear explosions, to show that ball lightning must be fed by an external energy source. Still others[21] showed that the simplest theory of ball lightning, based on heated spheres of air, predicted a luminous power exceeding 40W lasting for 6 seconds, although such a sphere would, of course, undergo convection and be subject to rapid power loss by convective mixing with the surrounding air.

Thus there is still no completely satisfactory theory to explain ball lightning. The best-developed, and still perhaps the most promising, models are the Powell-Finkelstein and Kapitsa models, both based on external sources of energy; the first describing a d.c., non-linear discharge, and the second describing an r.f. discharge.

The difficulty of constructing an entirely plausible theory may be caused by the unreliability of the observational data available concerning the phenomenon under study. Perhaps the experimental techniques described above may offer more reliable observations which may be used to test and modify the models.

CONCLUSIONS AND RECOMMENDATIONS

There has been a wide diversity of hypotheses to explain ball lightning, but there have been relatively few fully-developed models; none of these entirely explains the reported characteristics of ball lightning. This is partly because of the diversity of characteristics described in the 'folklore'.

We should also remember, before rejecting ball lightning out-of-hand, that although it is still regarded with much scepticism by the majority of the scientific community, discussion of it has recurred in scientific literature for well over a century.

One hundred and fifty years of scientific discussion on the subject of ball lightning have yet to produce conclusive evidence of its existence or nature. Although, even now, it cannot be claimed that the questions of the nature or even the existence of ball lightning have been firmly resolved, recent research in such fields as atmospheric physics, plasma physics and lightning research have contributed much to the forum of discussion on this topic.

Further studies of triggered lightning and photographic observation techniques used for studies of meteors and conventional lightning may provide useful information concerning ball lightning, and may help to establish its existence. Studies of eyewitness descriptions of alleged ball lightning events are likely to be useful only when these are provided within 24 hours of the event, or when physical traces remain after the event which may not be explained by other means.

REFERENCES

1. BARRY, J. D.: *Ball lightning and bead lightning; extreme forms of atmospheric electricity*, Plenum Press, New York and London, 1980.
2. STENHOFF, MARK: "Ball lightning", *Nature, 260,* (1976), p.596.
3. ARAGO, F.: "Sur le tonnerre", *Ann. Bureau des Longitudes, Notices Scientifiques,* (1838), p.221.
4. OLIVIER, C. P.: article entitled "Meteor", *Encyclopedia Americana,* 1965 edition, vol.18, p.713.
5. McNALLY, J. R.: "Preliminary report on ball lightning", *Oak Ridge National Lab., Report,* ORNL-3938, May 1966.
   RAYLE, W. D.: "Ball lightning characteristics", *NASA Tech. Note,* NASA-TN-D-3188, 1966.
6. DRAKE, F., in SAGAN, C. and PAGE, T. (editors): *"UFO's – a scientific debate",* Cornell University Press, Ithaca and London, 1972.
7. TOMPKINS, D. R., RODNEY, P. F. and GOODING, R.: "Photographic observations of ball lightning", *Bull. Am. Phys. Soc., 20,* (1975), p.659.
   TOMPKINS, D. R. and RODNEY, P. F.: "Possible photographic observation of ball lightning", *Nuovo Cimento C., 3C, 1,* (1980), p.200.
8. ERIKSSON, A. J.: "Video-tape recording of a possible ball lightning event", *Nature, 268,* (1977), p.35.
9. FIEUX, R., GARY, C. and HUBERT, P.: "Artificially triggered lightning above land", *Nature, 257,* (1975), p.212.
   HUBERT, P.: "Tentative pour observer la foudre en boule dans le voisinage d'eclairs déchlenchés artificiellement", *Rapport DPH/EP/76/349,* 5th May 1976, Commisariat á l'Energie Atomique, Service d'Electronique Physique.
10. FINKELSTEIN, D. and RUBENSTEIN, J.: "Ball lightning", *Phys. Rev., 135,* (1964), p.A390.
    POWELL, J. R. and FINKELSTEIN, D.: "Structure of ball lightning", in *Advances in Geophysics,* H. E. Landsberg and J. van Mieghes, ed., Academic Press, New York, 13, (1969), p.141; "Ball lightning", *American Scientist, 58,* (1970), p.262.
11. BRUCE, C. E. R.: "Ball lightning, stellar rotation and radio galaxies", *Engineer, 216,* (1963), p.1047; "Ball lightning", *IEE Journal (London), 9,* (1963), p.357.
    JOHNSON, P. O.: "Ball lightning and Self-containing Magnetic Fields", *Amer. J. Phys., 33,* (1965), p.119.
    RITCHIE, D. J.: "Ball Lightning – a Collection of Soviet Research in English Translation", *Consultants' Bureau, NY,* (1961).
    SHAFRANOV, V. D.: "On Magnetohydrodynamical Equilibrium Configurations", *Sov. Phys. JETP, 6,* (1957), p.545, also found in "Ball Lightning", D. J. Ritchie, ed., Consultants' Bureau, New York (1961); English translation of *Zh. Exsp. Teor. Fiz., SSSR, 33,* (1957), p.710.
    SILBERG, P. A.: "On the Question of Ball Lightning", *J. Appl. Phys., 32,* (1961), p.30; "Ball Lightning and Plasmoids", *J. Geophys. Res., 67,* (1962), p.4941; "Investigation of the Generation and Propagation of High-energy Spherical Plasmoids", *Aeronautical Systems Division, USAF, ASO-Tech. Document,* Report no. ASD-TDR-63-47, (October 1963); "A Standing Wave Discharge in Air", *J. Appl. Phys., 35,* (1964), p.2264; "A Review of Ball Lightning", in "Problems of Atmospheric and Space Electricity", S. C. Coroniti (ed.), *Elsevier, Amsterdam,* (1965), p.436; "A Note on the Formation of the Fireball Plasma", *J. Appl. Phys., 49(3),* (1978), p.1110.
    WOODING, E. R.: "Ball Lightning", *Nature, 199,* (1963), p.272; "Laser Analogue to Ball Lightning", *ibid., 239,* (1972), p.394.
12, 13: See SINGER, S.: "The nature of ball lightning", *Plenum Press,* New York and London, 1971, and reference 1 for numerous references on these theories.
14. ASHBY, D. E. T. F. and WHITEHEAD, C.: "Is ball lightning caused by antimatter meteorites?", *Nature, 230,* (1971), p.180.
15. KAPITSA, P. L.: "O Priroda Sharovoi Molnii", *Dokl. Akad. Nauk. SSSR, 101,* (1955), p.245; "Über die Natur des Kugelblitzes", *Phys. Blätter, 14,* (1958), p.11; "The Nature of Ball Lightning", in "Ball Lightning", D. J. Ritchie, ed., *Consultants' Bureau, New York,* (1961); "Elektronika Bol'shnik Moshchnostei", *Usp. Fiz. Nauk., 78,* (1962), p.181; "Sharovaya Moliniya I Radiozluchenie Lineinykh Molnii", *Zh. Tekh. Fiz., 38,* (1968), p.1829, English translation: "Ball Lightning and Radio Emission from Linear Lightning", *Sov. Phys. Tech. Phys., 13(11),* (1969), p.1475, English translation of *Sh. Tekh. Fiz., 38,* (1968), p.1829; "Free Plasma Filament in a High Frequency Field at High Pressure", *Sov. Phys. JETP, 30,* (1970), p.973, English translation of *Zh. Eksp. Teor. Fiz., 57(6),* (1969), p.1801; "A Thermonuclear Reactor with a Plasma Filament Freely Floating in a High Frequency Field", *Sov. Phys. JETP, 31,* (1970), p.973, English translation of *Zh. Eksp. Teor. Fiz., 58,* (1970), p.377.
16. PIERCE, E. T.: "Atmospherics and radio noise", in *Lightning: Vol.1: Physics of Lightning,* ed. R. H. Golde, Academic Press, London, New York and San Francisco, 1977.
17. KOSAREV, E. L. and SEREZHKIN, Yu G.: "Narrow band decimetre radiation from lightning", *Zh. Tekh. Fiz., 44,* (1974), p.361; *Sov. Phys. Tech. Phys., 19,* (1974), p.229.
18. TURMAN, B. N.: "Detection of Lightning Superbolts", *J. Geophys. Res., 82,* (1977), p.2566.
19. BERGER, K.: "The earth flash", in *Lightning: Vol.1: Physics of Lightning,* ed. R. H. Golde, Academic Press, London, New York and San Francisco, 1977.
20. SMIRNOV, B. M.: "Analysis of the Nature of Ball Lightning", *Sov. Phys. Usp., 18,* (1975), p.636, translation of *Usp. Fiz. Nauk, 116,* (1976), p.731.
21. LOWKE, J. J., UMAN, M. A. and LIEBERMANN, R. W.: "Toward a Theory of Ball Lightning", *J. Geophys. Res., 74,* (1969), p.6887.

THE MYSTERY OF SPIRAL-CIRCLE GROUND PATTERNS IN CROPS MADE BY A NATURAL ATMOSPHERIC-VORTEX PHENOMENON

By G. T. MEADEN

Abstract: We assess the evidence accumulated in recent years for the occurrence of descending atmospheric vortices which leave characteristic ground patterns in fields of growing crops. The damage areas are always spiral-centred and have generally circular symmetry with a sharp cut-off at the perimeter. Most of the traces we have investigated have been found on generally undulating ground and many were in lee situations close to hills. From this it appears that they are the result of plunging vortices created by lee-eddy effects.

Evidence for descending vortices in other situations is proposed as well, the origin being shear zones between air masses in turbulent weather. This may explain why at times similar spiral-circle traces develop in seemingly open-country situations.

BRIEF HISTORY OF THE DISCOVERY OF THE PHENOMENON

Our attention was first drawn to the spiral-circle problem in August 1980 when two circular areas of damage in a field of oats below the Westbury Hills at Bratton

Fig.1: Part of a spiral-centred circle showing the sharp separation between damaged and undamaged regions of the wheat crop.

Fig.2: A clockwise circle in wheat, Oxfordshire 1983.

were reported in the *Wiltshire Times.* The areas affected were seemingly circular and had been laid flat by a rotary force which had been strong enough to spiral the stalks in an outward clockwise direction. Despite the strength of the force, the stalks of the crop were not broken; they were simply bent over, having pivoted just above ground-level where they are weakest. Another unusual feature which set the origin of this phenomenon apart from that of more conventional wind-damage was the extremely sharp circular cut-off between the flattened and the untouched crop (cf Fig.1 for a later occasion).

Since then I have seen some 150 such circles, most of which I have photographed and about half of which I have surveyed with the co-operation of farmers and various friends and colleagues. From 1980 to 1985 I published a summary of each season's discoveries in the *Journal of Meteorology.* Being aware of the immense importance of the phenomenon, my expenditure of effort rose with each season and I travelled further and further afield in order to increase the rate of discovery of additional circles. The research was done in the summer as the crops grew and ripened, and the analysis was done in the winter. In the 1987 season between early May and early September a total of 66 circles were found by me or my friends in various parts of Wiltshire and Hampshire. Most of these circles were carefully surveyed and many were photographed from the air. The work of analysis continues and a lot remains to be done but it is now possible to present a summary embracing some of the features of this unusual and challenging problem. The majority of circles have been found on the Wessex chalk downs within a hundred kilometres of where I live, and it is because I repeatedly visit the sites already known to me that so many of the circles are reported from this region. There is no reason, however, to believe that the phenomenon is not a wholly general one, and already we have several reports of good circles from other countries, including in 1987 the foothills of the French Alps.

Fig.3: An anticlockwise circle of 1987 from north Wiltshire.

SINGLE CIRCLES

These are by far the commonest. They range from about 3 metres to 30 metres in diameter, and have spiral patterns which turn in either sense. It seems probable that the numbers of clockwise and anticlockwise spiral-circle formations may be about equal. For 1987, if we include every circle investigated as well as those which formed parts of complex sets, the numbers were divided as 36 anticlockwise and 30 clockwise.

The clockwise circle shown in Fig.2 was photographed in Oxfordshire in 1983. The ground in the picture looks fairly level but there is a steep escarpment facing north a couple of hundred metres behind the photographer.

The next figure (3) shows one of the anticlockwise circles of 1987 from north Wiltshire. In close-up (Fig.4) we give a photograph of an anticlockwise spiral

Fig.4: The centre of an anticlockwise circle.

Fig.5: A ringed circle with a plain single circle nearby (formed in rye, south Wiltshire).

centre (from a different circle). The tightness of the centre is remarkable. Sometimes the spiral centre coincides with the middle of the circle, but more often than not the gyrating centre undergoes a noticeable relative drift amounting to as much as a metre at times.

On two occasions known to us single spiral-circles have been witnessed during the course of formation (Meaden, 1985). The first observation was near Warminster in the 1970's in full view of numerous witnesses. Despite being formed in long grass rather than a cereal crop the pattern was rendered strongly enough that it was still there the next day. The flattening of the clockwise spiral was accompanied by a high-pitched humming sound and was completed in 'less than half a minute'. The other occasion was early in August 1983 when the formation of a circle was regarded while it flattened out a space in a field of wheat. The observer watched while the wheat was laid down in the typical fashion discussed and illustrated in this article, and he remarked how dust and debris were thrown up and outwards as well. Although the author has yet to have the good fortune to observe such an incident, he has observed on many occasions that when a freshly-made circle is inspected, especially in a dry, ripe crop, there is a scatter of broken straw and other light debris lying on top of the surrounding crop, but it takes only a light wind to rustle the crop for this useful evidence to sink out of sight.

RINGED CIRCLES

The spiral-centred circles are certainly formed by the descent of strongly rotating vortices, and their vortical origin is further confirmed by the occurrence of rings around some of them. Most common is the single-ringed circle (Fig.5). Within the ring the crop is always laid down in the opposite sense to the flow in the main circle, just as vortex theory would lead one to expect on account of momentum conservation requirements.

To date, only one case is known of a still rarer phenomenon – the double-ringed circle (Fig.6). The direction of flow in the outer ring was clockwise, as in the central circle, and opposite to that of the inner ring. However, there is a related type which appears to be a hybrid between the plain single-ringed and plain double-ringed types (see sketch in Fig.7). The fact that adjoining parts of the crop A and B are lying in opposite senses can only mean that one section of the crop was flattened to the ground before the other, and that the gyrating wind responsible for it then died away while the other expanded its diameter into the overlapping region.

THE WEATHER AND WIND AT THE TIME OF VORTEX FORMATION

Having investigated so many spiral-circles in the last eight years we have been fortunate to arrive at some of the sites within a few hours of their formation. In addition, as a result of interviews with land-owners and farmers it has proved possible to ascertain quite close limits as to the time of occurrence for some of the events. We are therefore able to say with complete assurance that circles have

Fig.6: Double-ringed circle formed in wheat, photographed from the air and the ground.

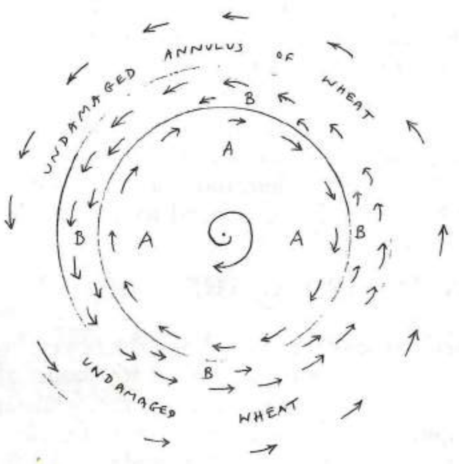


Fig.7: Sketch of hybrid overlapping rings (diameter of outer ring nearly 29 metres).

been known to form at night as well as by day, under cloudy skies as well as sunny skies, and in rainy conditions also. The phenomenon is therefore unlike the common heat-fuelled whirlwind which is composed of rising air and forms on sunny days, nor is it related to the type of ascending thermal whirlwind whose rotation is triggered by air-mass movements like sea-breeze fronts.

Instead, the vortex phenomenon is a previously-unrecognised effect resulting from the rapid downward movement of gyrating air. As Humphreys briefly but astutely remarked 50 years ago when explaining the origin of whirling vortices of powdery snow in the Antarctic described by Mawson (Humphreys 1940), such effects must have their origins at higher altitudes in a coexisting wind system, and from there they "burrow down, as vortices do, until plugged up by the surface beneath".

In short, our flattened circles originate from descending eddy currents, of which the best parallel for illustrative purposes is the common whirlpool. Whirlpools develop at particular points of a boundary zone in a liquid along which currents of differing densities or speeds meet, or beyond an obstacle like bridge piers where bifurcated currents reunite. From my observations in the floodwaters of the river at Bradford-on-Avon it seems that whirlpool formation is related to a sudden burst of speed of the currents. Obviously, for every descending whirlpool in a river there is a corresponding upwelling region (called a kolk or boil), the result of the incompressible water at the base of the whirlpool making its escape in a counterflowing current. Something similar must apply in the atmosphere and accounts for the raising of dust and debris as mentioned above.

John Heighes (1970) has reported vortices of intrinsically similar origin with his sightings of smoke vortices in the effluent-plume of the chimney of Reading Gas Works. His sketch (Fig.8) shows how the vertical, descending eddy vortex appeared beyond the chimney stack following an apparent surge in the release of the effluent which disrupted the previously dynamically-stable eddy system in the lee of the chimney.

This leads us to remark upon the spiral-circle formation in the lee of the isolated chalk hill known as Cley Hill in west Wiltshire. Fig.9 gives the position of spiral-circles known for the period 1982-87. For two of these we know the wind direction at the time the circles appeared. As this wind was westerly, this adds to the circumstantial evidence that an eddy effect is here involved.

The two short-lived, stationary snow-devils watched by Michael Cinderey in the lee of the Cleveland Hills on 27th January 1985 were certainly descending vortices of this same species (Cinderey 1985). The sky was almost overcast and the wind was rising fresh to strong south-south-east ahead of tempestuous weather. The snow-devils formed in almost the same spot with an interval of a few minutes and each lasted 10-15 seconds. It is but a logical step to surmise that the eddy vortices that produce the summer crop-patterns would be seen throughout the year if only powdery snow or a good growing crop was always available to serve as both sensor and tracer.

MULTIPLE PATTERNS

Circles sometimes form in sets or groups of two, three or five. The air photograph taken last summer is unusual in showing several groups close together (Fig.10). Besides the quintuplet set which shows up well despite the wheat having since been cut, there is a triplet and a doubled-doublet. This last began as a doublet when formed on 27th/28th July but the smaller of the circle pair was smothered a month later when another doublet came down in nearly the same place. As for quintuplet formation its symmetry speaks eloquently for the occurrence of some form of standing-wave interaction which couples the gyrating vortices as they spin in the atmosphere. In some quintuplets rotation has been found to be the same

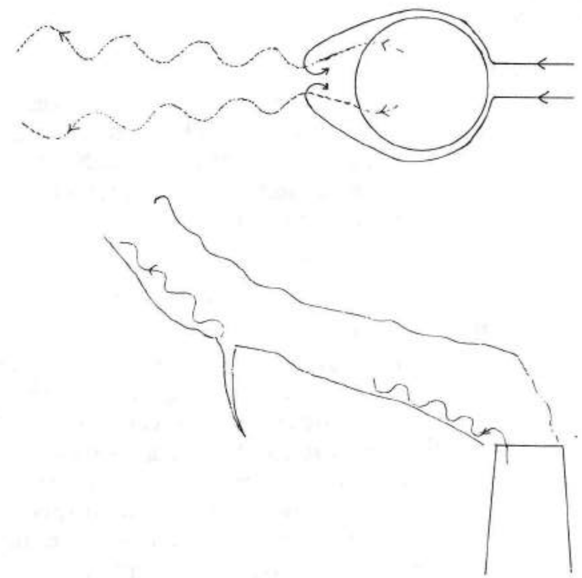


Fig.8: Eddy vortex formation in a smoke plume (after Heighes).

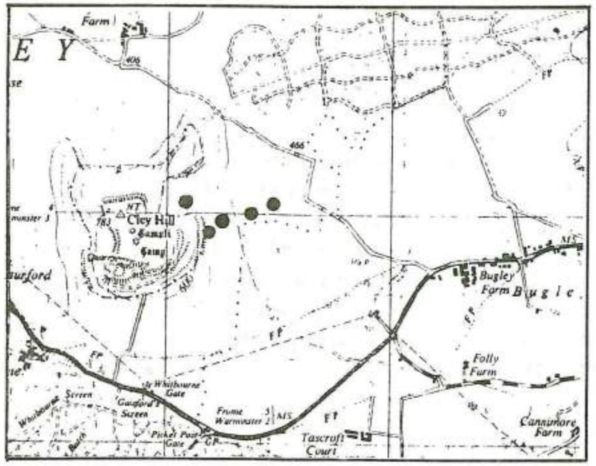


Fig.9: Map of the Cley Hill area showing the known crop-circle sites of 1982-1987.

in every circle (sets having all five circles clockwise are fairly common) but a mixture of the two senses of rotation happens as well. The quintuplet of the next figure (11) had four anticlockwise circles and one clockwise. Understanding the mathematics of the origins of such patterns should provide an interesting challenge to theoreticians.

There are certain other circle-types and matters regarding this phenomenon which could have been introduced as well but due to their complexity they must await further articles which are in preparation.

VIDEO FILM SEQUENCE

We next present a video film showing several of the formations which we have introduced in this paper and some others besides. The sequence begins with a plain circle followed by a ringed circle filmed from the ground. Next, from the air are seen a second ringed circle, some single circles, a quintuplet set, a triplet set, and a double-ringed circle. Lastly back on *terra firma* we visit the same single circles and the ringed circle which we had seen from the air.

DESCENDING VORTICES OF STATIONARY AND MOBILE TYPES – SUMMARY AND CONCLUSIONS

The crop-damage patterns are created by the rapid descent of atmospheric vortices which must have their origins in a coexisting wind system elsewhere. It is a forced-wind situation, the eddy vortices having very short lifetimes. Other vortex types with certain affinities to atmospheric eddies include visible smoke-plume vortices and the familiar whirlpool vortices seen in rivers, estuaries and coastal waters where currents of different densities and/or speeds mix.

We suggest that atmospheric eddy vortices which descend to the ground are a fairly common occurrence but they are usually invisible for want of adequate tracers. When they strike a farmer's crop, a distinctive trace is left which remains

conspicuous until the crop is harvested. Some of the crop-marks that we studied were to be seen three months afterwards, while others were removed by the combine harvester the day after formation. But when atmospheric vortices meet a water surface they can be seen (as a species of water-devil/spout) only during the few seconds while they last.

We have in fact a number of reports of events over water surfaces which seem to be of the eddy-vortex type. The clearest reports are those from inland lakes surrounded by hills or from coastal waters close to hills or cliffs where the vortices are generally described as 'waterspouts' or water-devils. Some of these have been classed as 'water-devils' (or waterspouts) in the past but their stationary character over water on cloudy days makes one suspect that some at least are not thermal whirlwinds of the ascending-air type but are descending vortices instead. Quite often such vortices appear as mobile or travelling vortices rather than stationary ones. Evidence for descending vortices of this type has appeared in letters from witnesses writing to TORRO, many of them in response to Mike Rowe's long-running press appeal for general whirlwind information from the public. As two examples we give: (1) 'Descending-vortex' waterspouts coming ashore on Slapton Sands (south Devon) and carving channels through reed banks and beach-shingle (31st January or 1st February 1972); (2) Numerous descriptions of repeated-event waterspouts on Scottish and English lakes and coastal waters in rough weather. On one occasion the water surface was so clearly depressed by the downward-spiralling motion in the centres of the 'waterspouts' that the witness called them 'whirlpools'.

Fig.10: Photograph of a circle-pocked 'lunar' landscape, 1987.

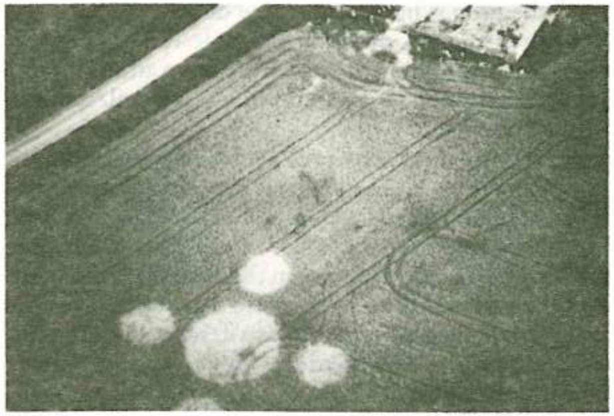


Fig.11: Quintuplet in a barley crop at Upton Scudamore, west Wiltshire, 1987.

Although many known cases seem to be definitely eddy-related, mountains or cliffs being nearby, it does look as though there can be occasions when descending vortices travel along zone boundaries between air-masses. Away from water surfaces the effect may resemble an invisible whirlwind with a primary circulation of descending damaging winds but devoid of a spout of condensed cloud or water drops. Invisible mobile vortices like these are probably quite common and may account for some reports of localised gusts of gale force or hurricane force which hitherto have been dismissed as 'squalls'. A recent example is the type of 'squall' incident described by David Reynolds at Wolverhampton for 7th February 1988 (private communication, to be published). Damage was local but severe and coincided with a minor trough of low pressure. The violent wind reached an extraordinary 95kt (109 mph) at a nearby anemometer and was the sort of incident that could be intrinsically similar to the invisible descending vortex of Humphrey's Antarctic snow-whirlwinds. When there is a very broad or spreading area of damage, one may speak of down-bursts, after Fujita, but it is not possible to do this if the damage trail is as short and narrow as a whirlwind track – in which event a vortex is the most likely means by which the energy can be localised sufficiently to create narrow-line hurricane-gust winds in what is otherwise a windfield of fairly low airspeed.

Descending vortices which traverse the countryside are possibly less uncommon than the stationary vortices, but I would expect *standing vortices* to develop at times in bad-weather conditions especially when there are buttresses or barriers, topographical or transient, to set up counterflowing forces that can lead to standing forced winds.

REFERENCES

CINDEREY, M. J. (1985): Stationary wind-devils in the January snow. *J. Meteorology, 10,* 339.
HEIGHES, J. M. (1970): Funnel cloud observations downwind from a chimney. *Weather, 25,* 289-290.
HUMPHREYS, W. J. (1940): *The Physics of the Air.* McGraw-Hill, New York.
MEADEN, G. T. (1985): Advances in the understanding of whirlwind spiral patterns in cereal fields. *J. Meteorology, 10,* 73-80.

WIND DAMAGE TO CARAVANS IN BRITAIN

By DEREK M. ELSOM
TORRO, Geography Unit, Oxford Polytechnic

Abstract: TORRO has documented numerous instances of caravans being damaged by strong winds. Many of these incidents have resulted in the occupants being injured or even killed. It is suggested that the provision of secure anchorage for static and touring caravans at caravan parks would drastically reduce the number of damage incidents and reduce the potential danger to occupants.

INTRODUCTION

Since TORRO began collecting details of local wind damage, whether the damage was due to tornadoes, thunderstorm downbursts or squall-line gusts, it has been noticeable that caravans frequently figure in the accounts of structural damage. Similarly, when gales occur, such as during the 15th-16th October 1987 storm, it is the caravan parks that most vividly depict the destruction wrought by high winds. Not only have there been many occasions when caravans have been severely damaged but also the occupants have been injured and, in a few incidents, an occupant has been killed.

WIND DAMAGE TO CARAVANS

It is not surprising that caravans suffer damage from high winds. Caravans have a relatively large surface-area to weight ratio and so they are readily overturned by winds of about 60 mph (27 m/sec) or more (American Meteorological Society, 1985). However, what is evident is that if the caravans had been anchored, then on many cases no damage would have occurred. Of course, there is a threshold wind

Fig.1: Destruction of the caravan park at Peacehaven in Sussex by the great storm of 15th-16th October 1987. Over 200 caravans were wrecked. *(Brighton Evening Argus).*

Fig.2: Nine people were taken to hospital and 152 caravans overturned and damaged by a force T3 tornado at Winthorpe, near Skegness, Lincolnshire, on 27th September 1968.

speed that will damage even an anchored caravan (the anchorage fails or the caravan roof is stripped away) but that leaves many incidents when anchorage would have prevented any damage.

Caravans (and mobile homes) are potentially dangerous structures. Although caravans can withstand simply being toppled on to one side, few can withstand lifting and/or repeated rolling. Nor can caravans withstand an impact against another caravan or a building.

INJURY AND DEATH

A Building Research Establishment survey of local and national newspaper reports of damage to buildings for the period 1962-81 found that wind damage to caravans/mobile homes led to 4 deaths, one major injury (stay in hospital) and 47 minor injuries (Cook, 1984). Approximately one-quarter of all the injuries were ascribed to the caravans being damaged by tornadoes (Buller, 1985). The recorded deaths and injuries occurred because caravans were overturned or wrecked or, in a few cases, because a tree fell on to the caravan. Inevitably, such figures underestimate the true situation.

Anchorage of caravans would reduce the potential for injuries due to occupied caravans being toppled, rolled and lifted or even crushed. Of course, anchorage does not reduce the vulnerability of a caravan to flying debris through its thin walls, but at least other anchored caravans would not add to the flying debris through being damaged.

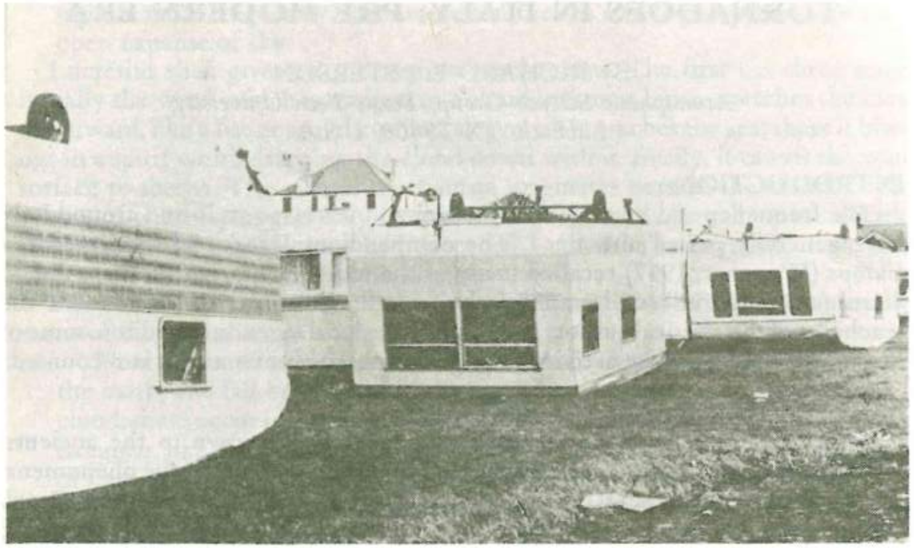


Fig.3: Seventeen caravans were wrecked or severely damaged and three people were injured at Sunnysands Caravan Park by the force T3-4 tornado at Barmouth, Gwynedd, on 4th October 1985 (Robin Harper).

RECOMMENDATION

As a means of reducing the number of incidents when caravans may be damaged by strong winds, and to reduce the risk of injury to occupants, all static caravans on caravan parks should be securely anchored. Anchorage facilities should also be provided for touring caravans using caravan parks. Further, to reduce the potential of injury, it is recommended that caravans should be temporarily vacated for the security of a stronger building when a warning of severe gales is issued by the Meteorological Office.

REFERENCES

AMERICAN METEOROLOGICAL SOCIETY (1985): Mobile homes and severe windstorms. *Bull. Amer. Met. Soc., 66,* 857.

BULLER, P. S. J. (1985): Structural damage caused by tornadoes in the United Kingdom. *J. Meteorology, 10,* 221-226.

COOK, N. J. (1984): Performance of buildings in the United Kingdom. *Eng. Struct., 6,* 248-255.

SEVERE WEATHER
A Video Film Presentation

By JOHN M. HEIGHES

Among the video tapes presented are sequences showing the Minneapolis tornado funnel of 18th July 1986 which were taken from a following helicopter.

As well as damage scenes and eye-witness accounts of the Selsey and Lewes tornadoes of 20th-21st November 1986 and the Great Storm of 15th-16th October 1987, other types of vortices including fire-whirlwinds will be shown.

TORNADOES IN ITALY: PRE MODERN ERA

By RICHARD E. PETERSON
Atmospheric Science Group, Texas Tech University,
Lubbock, TX 79409, U.S.A.

INTRODUCTION

The frequency and severity of tornadoes and waterspouts in and around Italy have generally passed unnoticed. The compendious *Wind- und Wasserhosen in Europa* (Wegener, 1917) recalled many of the older events, but (perhaps due to wartime limitations) underrated Italy overall. This survey summarises the teachings of the classical authors and some of the local legends; in additon, some of the evidence of tornadic activity during the subsequent centuries is recounted.

EARLY SCIENCE AND LEGENDS

Tornadoes, waterspouts and dust devils were well known to the ancients; virtually all of the classical philosophers provided explanations of the phenomena. For the most part, the Roman authors accepted the views of their Greek predecessors, of whom more than twenty, according to Pliny, had produced meteorological treatises. Aristotle's *Meteorologica* is perhaps the most renowned exposition of natural phenomena from the Greek philosophers; however his interpretations of nature did not constitute the only tradition.

The Epicurean materialist view of the universe was reflected in *De Rerum Natura* (On the Nature of the Universe) by Titus Lucretius Carus (90's-50's BC). The first 534 lines of Book 6 are devoted to meteorology; lines 423-450 treat whirlwinds and waterspouts:

> . . . it is easy to understand what force flings down into the sea those waterspouts which the Greeks aptly term *presteres* or 'scorchers'. It sometimes happens that a sort of pillar descends into the sea as though let down from above. Around it the waters boil, lashed by madly blowing blasts, and woe to any ship that is embroiled in this hurly-burly.
>
> This is sometimes brought about when a prisoned wind fails to burst a cloud it has possessed but forces it downwards. So it sags down like a pillar lowered into the sea out of the sky – gradually, like something pushed from above by a fist at the end of an out thrust arm and so protruding down into the waves. When the wind has burst this bulge, out it rushes into the sea and creates a bewildering stir among the waves. The cloud, in fact, with its elastic structure is forced down by an eddying whirlwind, which descends with it. As soon as its teeming bulk has been pushed down to sea level, the wind is suddenly let loose into the water and stirs up all the sea making it seethe and roar terrifically.
>
> It sometimes happens also that an eddy of wind wraps itself in clouds through scraping together atoms of cloud out of the air, and mimics a *prester* let down out of the sky.
>
> When a waterspout drops on dry land and there explodes, it disgorges a violent vortex of swirling wind. But, since this happens in any case but seldom, and on land our view of it must often be blocked by mountains, the sight is more frequently encountered in the sea's wide prospect under an open expanse of sky . . "

Lucretius then gives two formation mechanisms. The first has three stages: initially the wind, which is trapped in a cloud it cannot burst, stretches the cloud downward, like a fist or arm thrust in a sleeve, till it reaches the sea; there it bursts out in a spirit whirl, dragging the cloud down with it; finally, it causes the water surface to seethe. The second mechanism originates outside the cloud: a spiral vortex of wind forms and only later involves the cloud. Actually more detailed distinctions and explanations had preceded Lucretius; he seems to have been rather eclectic or confused in his choice.

Pliny the Elder (23-79 AD) in his *Natural History* (Book II, 131-134) recalled more of the earlier ideas:

> Now as to sudden blasts, which arise as has been said from exhalations of the earth, and fall back again to the earth drawing over it an envelope of cloud; these occur in a variety of forms. The fact is that their onrush is quite irregular, like that of mountain torrents (as we have pointed out in the view of certain persons), and they give forth thunder (tonitrua) and lightning (fulgura). If travelling with a heavier momentum they burst a great gap in a dry cloud, they produce a storm (procellam) called by the Greeks a cloudburst (ecnephias); but if they break out from a downward curve of cloud with a more limited rotation, they cause a whirl (verticem) unaccompanied by fire (fulmine) – I mean by lightning – that is called a typhoon (typhon), which denotes a whirling cloudburst. This brings down with it a portion of heat torn from a cloud, which it turns and whirls round, increasing its own downward velocity by its weight, and shifting from place to place with a rapid whirl (vertigine); it is specially disastrous to navigators, as it twists round and shatters not only the yeards, but the vessels themselves, leaving only the slender remedy of pouring out vinegar (aceti) in advance of its approach, vinegar being a very cold substance. The same whirlwind when beaten back by its very impact snatches things up and carries them back with it to the sky, sucking them high aloft.
>
> But if it bursts out of a larger cavern of downward-pressing cloud but not so wide a one as in the case of a storm, and is accompanied by a crashing noise, this is what they call a whirlwind (turbinem) which overthrows everything in the neighbourhood. When the same rages hotter and with a fiery flow, it is called a *prester,* as while sweeping away the things it comes in contact with it also scorches them up. But a typhoon does not occur with a northerly wind, nor a cloudburst with snow or when snow is lying. If it flared up as soon as it burst the cloud, and had fire in it, did not catch fire afterwards, it is a thunderbolt (fulmen). It differs from a fiery pillar (prester) in the way in which a flame differs from a fire: a fiery pillar spread out its blast widely, whereas a thunderbolt masses together its onrush. On the other hand a tornado (vertex) differs from a whirlwind (turbine) by returning, and as a whizz differs from a crash; a storm is different from either in its extent – it is caused by the scattering rather than the bursting of a cloud. There also occurs a darkness caused by a cloud shaped like a wild monster – that is direful to sailors. There is also what is called a column,

when densified and stiffened moisture raises itself aloft; in the same class also is a waterspout (silon), when a cloud draws up water like a pipe.

The following legend is recounted by Giammarco (1963): "A young woman became a *scijone* (waterspout) and came ashore one day at Ortona. When the storm was over, an old man saw some boys badgering a serpent, having removed one of its eyes. Moved to pity, he rescued the serpent from its persecution. After some years, the old man was at Ancona for the festival of San Ciriaco and at the window of a palace he saw a beautiful young woman who was blind in one eye. When she saw him, she stopped and greeted him, expressing immense gratitude for having been saved from certain death on that day when, in the form of a serpent, boys had thrown stones at her".

There is a widespread belief that waterspouts are beings who by black magic have the privilege of performing evil acts, like witches and werewolves and that they are born on Christmas Eve. Many fishermen believe they are empowered by the devil. The fishermen believe that the creatures which have been transformed into waterspouts will be freed forever if they are cut off or simply wounded. Even today sailors are always supplied with a black-handled knife, called *la cultèllë di sandë Libbòrië*. The method of "cutting the cyclone" varies. At Vasto a fisherman draws with the knife the sign of Solomon with five points – the head, arms and feet – reciting a ritual formula at each point. Then he throws the knife at the figure; the waterspout breaks in two if the figure is hit in the centre. The sailors of Francavilla simply trace a cross in the air with the knife in the direction of the spout while saying a prayer.

At Ortona, the captain of a boat, after crossing himself and having recited an Our Father and a Hail Mary to St. Paolo, patron of storms, traces the seal of Solomon with the dagger. Then he says: "I see you and may God dispel you." If there is a first born on the boat, the captain enjoins him to perform the ritual.

Also a preferred practice is to wield a dagger making the sign of the cross and then with the blade edgeways cutting a part of the boat somewhere; in the case that two brothers are on board the elder performs the rite, otherwise the captain. At the sight of the funnel, the sailors let loose all forms of obscenities, believing in this way to show their contempt for this perversion of nature. At Termol, the sails are lowered and the captain lowers his pants and turns toward the waterspout to demonstrate his contempt.

The Italian explorer and navigator Christopher Colombo, on his fourth voyage in 1502 encountered a waterspout:

> And besides all these various terrors there occurred another no less dangerous and astonishing, a waterspout which on Tuesday 13th December passed among the ships, which had they not cut by saying the Gospel according to St. John, as there is no doubt that whomsoever it fell upon would have been drowned. For it draws the water up to the clouds in the form of a pillar thicker than a hogshead, twisting it about like a whirlwind.

The Gospel referred to is John vi 17-20 ending "Ego sum, nolite timere" ("Fear not, for it is I"). Herrera (*Historia general de las Indias,* I, lib v, ch 3) describes, perhaps from imagination but possibly from oral tradition, how Columbus exorcised the waterspout by reading these verses and describing with his sword a circle in the air

around his feet (Morison, 1963).

Waterspouts are designated by various words, with differing pronunciations. In the Adriatic, in addition to *trombe marine,* the common terms are *sifone* (siphon), *ciclone, scijone* (cyclone), *cifere* (lucifer), *dragu* (dragon), *rahane* (hurricane), *vishdurne* and *vutarelle* (Giammarco, 1963). In the Tyrrhenian area the terms for waterspout include *seillon.* Near Venice they are called *bisciabuova.*

Through the Middle Ages, authors generally repeated the explanations offered by Lucretius, Pliny and Seneca. During the thirteenth century, individual cases appear, mostly regarding damage and the miraculous salvation of people (Hellmann, 1917). One brief account referred to a tornado in 1410 at Venice; Leonardo da Vinci noted another (Pike, 1988).

A notable treatise on tornadoes was published in 1555 by Olaus Magnus, however it was largely dependent on Seneca and Vincentius Bellovacensis (*Spec. nat.,* Liber V, cap 39; De turbine). Actual scientific investigation did not begin for another hundred years (Hellmann, 1917).

EARLY ACCOUNTS OF SPECIFIC STORMS

Ancona 1456

The earliest Italian tornado for which detailed accounts exist occurred in 1456. In their histories of Florence the event is mentioned in 1532 by Machiavelli and more completely described by Ammirati.

According to Machiavelli:

> On the twenty-fourth of August, about an hour before daybreak, there arose from the Adriatic near Ancona, a whirlwind, which crossing Italy from east to west, again reached the sea near Pisa, accompanied by thick clouds, and the most intense and impenetrable darkness, covering a breadth of about two miles in the direction of its course. Under some natural or supernatural influence, this vast and overcharged volume of condensed vapor burst; its fragments contended with indescribable fury, and huge bodies sometimes ascending toward heaven, and sometimes precipitated on the earth, struggled, as it were in mutual conflict, whirling in circles with intense velocity, and accompanied by winds, impetuous beyond all conception; while flashes of awful brilliancy, and murky, lurid flames incessantly broke forth. From these confused clouds, furious winds, and momentary fires, sounds issued, of which no earthquake or thunder ever heard could afford the least idea; striking such awe into all, that it was thought the end of the world had arrived, that the earth, waters, heavens, and entire universe, mingling together, were being resolved into their ancient chaos. Wherever this awful tempest passed, it produced unprecedented and marvellous effects; but these were more especially experienced near the castle of St. Casciano, about eight miles from Florence, upon the hill which separates the valleys of Pisa and Grieve. Between this castle and the Borgo St. Andrea, upon the same hill, the tempest passed without touching the latter, and in the former, only threw down some of the battlements and chimneys of a few houses; but in the space between them, it levelled many buildings quite to the ground. The roofs of the churches of St. Martin, at Bagnolo, and Santa Maria della Pace,

were carried more than a mile, unbroken as when upon their respective edifices. A muleteer and his beasts were driven from the road into the adjoining valley and found dead. All the large oaks and lofty trees which could not bend beneath its influence, were not only stripped of their branches but borne to a great distance from the places where they grew, and when the tempest had passed over and daylight made the desolation visible, the inhabitants were transfixed with dismay. The country had lost all its habitable character; churches and dwellings were laid in heaps; nothing was heard but the lamentations of those whose cattle or friends were buried beneath the ruins; and all who witnessed the scene were filled with anguish or compassion . . .

Ammirati puts the storm on the twenty-second and furthermore limits its path to 20km. In addition however he notes that the houses were not destroyed in their entirety, but rather sections were separated and transported by the wind. At one point, a high wall was overturned, half of it to the north, the other half toward the south. Along the path, a farmer had stored several bushels of grain in his house; without damage to the dwelling, all the grain was removed through shuttered windows. At another point a basket of grain was carried into a field where it was set down without a loss of grain.

Venice 1686

The first published drawing of a waterspout was of an observation by de Monconys 31st December 1648 near Sardinia, published in 1665, One of the earliest detailed studies of a tornado appeared in 1694: *Le forze d'Eolo.* Dialogo fisico-matematico sopra gli effeti del vortice, o sia turbine, detto negli Stati Veneti la bisciabuova. Che il giorno 29 Luglio 1686 ha scorso, e flagellato molte ville, e luoghi de'territorj di Mantova, Padova, Verona, etc. Opera postuma del Sig. Dottore Geminiano Montanari Modanese, Astronomo e Meteorista dello Studio di Padova. In Parma, ad instanza d'Andrea Poletti.

The tornado struck in the State of Venice about 5.00 p.m. 29th July 1686. Disabled by a light stroke, Dr. Montanari, astronomer and meteorologist at Padua, was unable to trace the damage himself; instead his colleague Professor Spoleti performed the path analysis. The tornado began south-west of Venice near Legnago and moved north-eastwards to east of Padua, a distance of 65km (another account indicates 80km). The duration was about an hour with the translation speed steadily increasing; Spoleti gives a path width of ½-1 mi (one Italian mile is about 1855m). Apparently too the strength and destruction increased during the tornado lifetime. Figures are included as well.

Most of the volume is taken up with theoretical discussions; it contains an attempt, for example, to calculate the pressure exerted by a tornado advancing at a known speed; the whole discussion is rather involved since it is cast in the form of a dialogue (with Abbot Davia and Canon Gozzadini). Mention is made of several other tornadoes during the previous forty years in the region around Venice. Montanari noted the superstition of cutting the waterspout with a black handled dagger; instead he advocated the rational use of artillery! Montanari actually passed away (29th July 1687) before completing the work, so the conclusion was written by his pupil Abbot Francesco Bianchini.

Rome 1749

One other investigation must be mentioned, for it received wide attention. On the night of 11th June 1749, a waterspout moved eastwards out of the Tyrrhenian Sea becoming a tornado and paralleling the Tiber from Ostia to Rome. After a three-week study and at the behest of Cardinal Valenti, the renowned physicist Fr. Boscovich wrote *Sopra il turbine che la notte tra gli XI e XII Giugno del 1749 dannegio una gran parte di Roma.* Dissertatione del P. Ruggiero Guiseppe Boscovich della Compania di Gesu dedicata a sua Emmenza il Signor Cardinale Silvio Valenti Segretario di Stato e Camerlengo di Santa Chiea, in Roma, 1749.

The book may be divided into 3 sections: the damages at Rome; a history of other tornadoes; and finally a discussion of tornado theories. Another, anonymous account appeared in Florence in 1749 with the title *Relazione del fiero e spaventoso turbine accaduto in Roma la notte del di 11 giugno del corrente anno 1749,* based on letters.

Meteorological conditions in the days preceding the tornado were quite unsettled, with heavy thunderstorms and hail. On the evening of 11th June a violent storm was seen and heard toward the sea, although only drizzle (with very small hail) fell in Rome before the tornado struck in the city.

Few details are available on the tornado before it reached Rome; the damage investigation was confined to the city. However, several cottages and more substantial buildings were damaged in Ostia.

The tornado crossed the south-east corner of Rome beginning about 6.45 p.m. between Porta Ardeatina and Porta S. Paolo. It moved back into the countryside near the ancient Castrum Praetorium. Its ultimate path is unknown, but it apparently proceeded to near Cas. Redicicoli, a distance of 43km from the sea.

Boscovich enumerated the effects of the winds in great detail. Along the path nothing went undamaged, trees, walls, roofs, doors, windows, and pavement. In many places the rotary movement within the vortex was evident due to the contrary position of fallen trees and walls. Many objects were thrown a great distance; for example, a portion of a roof landed 225m away. At some places damage completely to the ground had a breadth of 22m; more generally the damage was about 50m across. The irregular pattern of damage with some buildings spared was explained as due to the tornado splitting into secondary vortices. Desio (1925) suggests that instead the effect may be produced by the presence of large projectiles.

The second and third parts of the book are devoted to a comparison between the Rome tornado and earlier events, and to the origin of tornadoes in general. Among others, he recalls the accounts of Machiavelli, Montanari *et al.* On the theoretical side, he primarily sets down the ideas of the ancients, attributing modern terms to the old concepts. He goes on to explain unusual rains as due to the dispersal of material by a whirlwind somewhere. Furthermore, he explains the presence of marine fossils in mountainous regions as due to the transport by tornadoes! He attempted to calculate the maximum height to which a column of water could be lifted and the velocity of rotation of the 1749 tornado (110 m/s). Ludlam (1963) has emphasised the importance of this report in the formulation in 1765 of a conceptual waterspout model by Benjamin Franklin.

CONCLUSION

There have been significant advances in the understanding of the tornado phenomenon due to scholars based in Italy from the earliest times. Outstanding tornado occurrences across Italy through the centuries have prompted this intellectual development. (The accompanying table lists some of those mentioned in the literature before 1920). Even though Italian meteorologists have not devoted considerable attention to tornadic activity several outstanding recent events have been documented; a review and synthesis of those storm situations will appear elsewhere.

TABLE 1: Specific Tornadoes and Waterspouts in and around Italy up to 1919.

Date	*Location*	*Source**
1410	Venice	Hellmann
24 Aug. 1456	Ancona-Pisa	Macchiavelli
1556	Malta	de Boisgelin
24 Aug. 1617	Rome	Desio
9 Jan. 1637	Rome	Desio
4 Dec. 1645	Rome	Desio
31 Dec. 1648	Sardinia	Hellmann
29 June 1650	Venice	Montanari
9 Aug. 1653	Rome	Desio
1660	Venice	Montanari
12 May 1668	Venice	Montanari
1679	Venice	Montanari
29 July 1686	Verona	Montanari
1686	Po	Desio
7 Aug. 1701	Mediterranean	Peltier
1710	Dalmatia	Peltier
Fall 1733	Ancona	Boscovich
1736	Mediterranean	Peltier
1742	Venice	Boscovich
17 June 1745	So France	Boscovich
29 Aug. 1747	Livorno	Peltier
21 May 1748	Arezzo	Boscovich
11 June 1749	Rome	Boscovich
Aug. 1756	Gibraltar	Peltier
29 Oct. 1757	Malta	Peltier
23 Aug. 1785	Adriatic	Rossman
30 June 1794	Vesuvius	Muncke
22 Nov. 1796	Tenerife	Peltier
30 July 1804	Viguzzolo	Peltier
30 July 1806	Palmanova	Wegener
14 Aug. 1817	Naples	Peltier
16 Sept. 1823	Valeggia	Peltier
27 June 1827	Sicily	Wegener
29 Oct. 1832	Malta	Peltier
1 Nov. 1832	Ionian Sea	Peltier
23 Dec. 1832	Vesuvius	Reye
1832	Mediterranean	Peltier
1 Oct. 1834	Etna	Peltier
June 1850	Vesuvius	Reye
July 1863	Naples	Wegener
8 Apr. 1866	Santorin	Reye
Oct. 1869	Kotor Bay	Wegener
19 Sept. 1872	Fiume	Wegener
1884	Catania	Desio
21 Sept. 1897	Orla	Desio
8 June 1913	Buttrio	Desio
1915	Friuli	Desio
30 Aug. 1919	Friuli	Desio

**mentioned in the text or cited in the references.*

REFERENCES

DE BOISGELIN, L. (1802): *Ancient and Modern Malta.* Vol.2, London, 59-61.

DESIO, A. (1925): Su un turbine atmosferico che investi Roma nel 1749. *Riv. Geogr. Ital., 30,* 156-162.

GIAMMORCO, E. (1963): *Lessico marinaresco abruzze e molisano.* Venice.

HELLMANN, G. (1917): Die ältesten Untersuchungen über Windhose. *Beitr. Geschichte Meteor., 2,* 329-334.

LUDLAM, D. M. (1970): *Early American Tornadoes.* Amer. Meteor. Soc., Boston, 138-142.

MORISON, S. (1963): *Journals and Other Documents on the Life and Voyages of Christofer Columbus.* Heritage Press, p.399.

MUNCKE, ... (1842): Wettersäule, in *Gehler's Physikalische Wörterbuch, 10.* Leipzig, 1635-1723.

PELTIER, A. (1840): *Météorologie Observations et recherches expérimentales sur les causes qui concourent a la formation des trombes.* Paris, p.444.

PIKE, W. S. (1988): A note on Leonardo's tornado (late 15th – early 16th century). *J. Meteorology (U.K.), 13.* 223-224.

REYE, T. (1872): *Die Wirbelsturme, Tornados und Wettersaulen.* Hannover, 247p.

ROSSMANN, R. (1953): The physical process in the development of tornadoes and consequences which influence their dissipation. *Conf. Radio Meteor.,* Univ. Texas, X-7, 1-10.

WEGENER, A. (1917): *Wind- und Wasserhosen in Europa.* Braunschweig, p.301. REYE, T. (1872): *Die Wirbelsturme, Tornadoes und Wettersaulen in der Erd-Atmosphere mit Berucksichtigung der Sturme in der Sonnen-Atmosphere.* Hannover, 247p.

A NOTE ON LEONARDO'S TORNADO (LATE 15th - EARLY 16th CENTURY)

By W. S. PIKE

19 Inholmes Common, Woodlands St. Mary, Newbury, Berkshire RG16 7SX

Terence Meaden (1985), in referring to an interesting sketch of a tornado cloud seen at Augsberg on 2nd July 1587, asked "Are any older drawings of tornadoes known to exist?" (p.15). It may be mentioned that, while less specific in precise dating and scientific content, Leonardo da Vinci's drawing (dating from ca.1518 or 1519; shown in Fig.1) of the effects of a tornado-producing storm most probably seen near Milan, certainly pre-dates the Augsberg sketch.

Leonardo (1452-1519) was drawing from a combination of imagination and memory when he produced this work in France, sometime during the last two years of his life. Broken trees are strewn around with horses and riders left upset and sprawling on the ground following the tornado's passage (bottom right of picture). Above this scene of disorder, the retreating funnel-cloud is represented in bodily form by a masculine, partly-demonic, partly-cherubic 'wind god': this perhaps suggesting that Leonardo felt Nature had played a naughty and savage trick on those below.

It seems distinctly probable that, on one of his frequent journeys, Leonardo personally witnessed the power of a tornado at some date prior to 1508 when his following animated quotation was published in *Paris, Institut de France:–*

"I once observed a cloud shaped like a huge mountain over Milan which

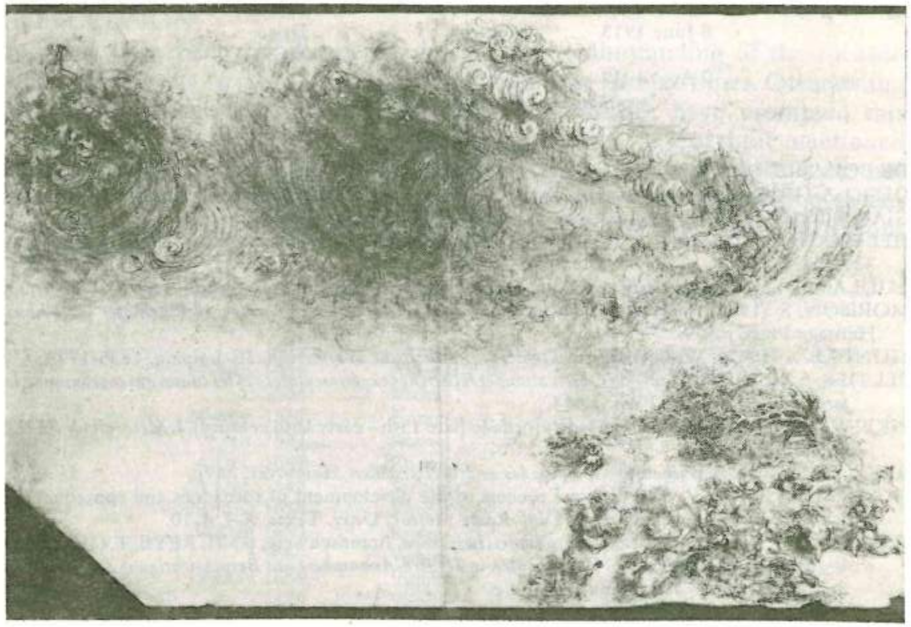


Fig.1: "Tornado over Horsemen and Trees" by Leonardo da Vinci ca.1518-1519. Pen and ink over black chalk with touches of colour wash and traces of white, on grey-washed paper. Serial number RL 12376 is 41cm across by 27cm high. Copyright permission by the Royal Library (Rights and Reproductions), Windsor Castle, on behalf of the Queen.

caused a tremendous storm of wind and a hollow column of air which excavated a gravel pit with its vortex motion and transported gravel, sand and water more than half a mile through the air".

The drawing-materials used (especially the grey-wash preparation of the paper) suggest it was made during Leonardo's 'French period' after 1517, and this drawing now bears serial number RL 12376 at The Royal Library, Windsor Castle, where it is kept as one of a series known as the 'Deluge Drawings'. Several of these late works were thought to have been inspired by reports of a huge landslide and flooding in The Alps during 1515, known as 'The Bellinzona Disaster' due to a considerable loss of life there.

Although the drawing is usually referred to as "Hurricane . . .", perhaps a more apt title would be "*Tornado* over Horsemen and Trees".

Acknowledgement

Thanks are due to Miss Henrietta McBurney, Deputy Curator of the Print Room, Royal Library Windsor Castle, for kindly sending notes on Leonardo's "Symbolic Landscapes and Deluge Series" of drawings, and to Miss Anne Williams of Rights and Reproductions, for arranging for the reproduction of the print.

REFERENCE

MEADEN, G. T. (1985): A Sixteenth Century Sketch of a Tornado Cloud, Augsberg, Germany, 2nd July 1587. *J. Meteorology, U.K., 10,* No.95, pp.15-16.