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Monitoring the homogeneity of UK climatological data

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Summary

UK temperature and sunshine data have been monitored for homogeneity during the period 1951–80. Of the stations investigated 34% were flagged as containing inhomogeneities, the majority being gradual changes for which corrections could not easily be made. These findings have implications for the World Meteorological Organization concept of Reference Climatological Stations and the use of individual stations for the monitoring of climatic trends.

Introduction

The need to monitor climatic change has increased in importance in recent years because of interest in the possible impact of man on the environment. The study of climatic trends requires long records of representative climatological data with any inhomogeneities eliminated, while the production of long-period statistics also requires homogeneous series of data.

The World Meteorological Organization (WMO) has recommended the nomination of Reference Climatological Stations whose data could be used to determine climatic trends. The *Manual on the Global Observing System* (WMO 1981) states that such stations require at least 30 years of homogeneous records, where man-made environmental changes have remained, or are expected to remain, at a minimum. In the United Kingdom the original reference stations were based on Principal Climatological Stations, mostly Meteorological Office-staffed synoptic observing stations, where high observing standards would be maintained. In 1982 this list was revised to comprise 21 long-period stations, both voluntary and officially manned, with minimal changes in site. The homogeneity of none of these reference stations was checked at the time owing to the difficulties of analysing such long periods of data by hand. However, daily climatological data are available in machinable form for most stations from 1959 and, for the purposes of creating the 1951–80 averages, monthly data were entered in the computer archives for 214 stations from 1951 to 1958. The aim of this paper is to describe a routine to monitor the homogeneity of stations with at least 10 years' data in the period 1951–80. There were 577 such stations for temperatures and 391 for sunshine.

Detection of inhomogeneities

Estimated values of climatological data at a station may be derived using regression techniques with selected near neighbours or by performing Principal Component Analysis (Crummay 1985). The latter technique was selected for this application since the near-neighbour approach may place too much weight on individual stations, which may themselves contain inhomogeneities.

Principal Component Analysis, as described by Kendall (1975), enables fields of correlated data to be represented by a set of orthogonal patterns, or eigenvectors, each explaining the greatest part of the remaining variance. The leading components represent systematic differences between the variables while random differences are consigned to higher-order components. This application of Principal Component Analysis is discussed by Spackman and Singleton (1982) and in more detail by Spackman (1979, 1980). By selecting an optimum number of components, it is possible to isolate the systematic differences and use these as estimates for comparison with the genuine observations.

The complete, self-consistent correlation or covariance matrix required was derived from a data set of monthly values created as part of the preparation of averages for the period 1951–80, any missing values having been estimated using the near-neighbour technique described by Tabony (1983).

The optimum number of components to use was determined by an investigation of known inhomogeneities identified by Done (1980). The majority of these were detected when the number of components equalled 8% of the number of stations for temperature and 12% for sunshine. The higher percentage for sunshine is a reflection of the lower inter-station correlation compared to that observed for temperature.

Residuals (observations minus estimates) were derived and divided into two subsets whose means were compared using 'Student's' *t*-test. Simply dividing the residuals into two halves would not permit the detection of inhomogeneities near the beginning and end of the record. The *t*-test was therefore performed five times with the data divided as follows to identify the approximate location of any changes:

	Subset 1	Subset 2
(i)	First 5 years (60 residuals)	last 25 years (300 residuals)
(ii)	First 10 years	last 20 years
(iii)	First 15 years	last 15 years
(iv)	First 20 years	last 10 years
(v)	First 25 years	last 5 years

Only genuine observations (as opposed to estimates) were used and queries raised when the difference in mean values of the two subsections exceeded the 95% confidence limit. To identify the specific years in which inhomogeneities occurred and to aid clarity, the annual means of the residuals were plotted, as shown in Figs 1 and 2. This application of the *t*-test is relative rather than absolute, however, as illustrated by the following points:

(i) The level of statistical significance is dependent on the amount of data available, e.g. a difference of 0.01 °C can become significant with a long enough record. The testing will therefore preferentially 'pass' stations with a short series of observations.

(ii) The routine is more likely to identify inhomogeneities in the middle of a record than those at the end.

(iii) Stations with a poor standard of observations, and hence a large 'noise' level, are more likely to be passed by the routine than a station with high observing standards and a small but steady trend.

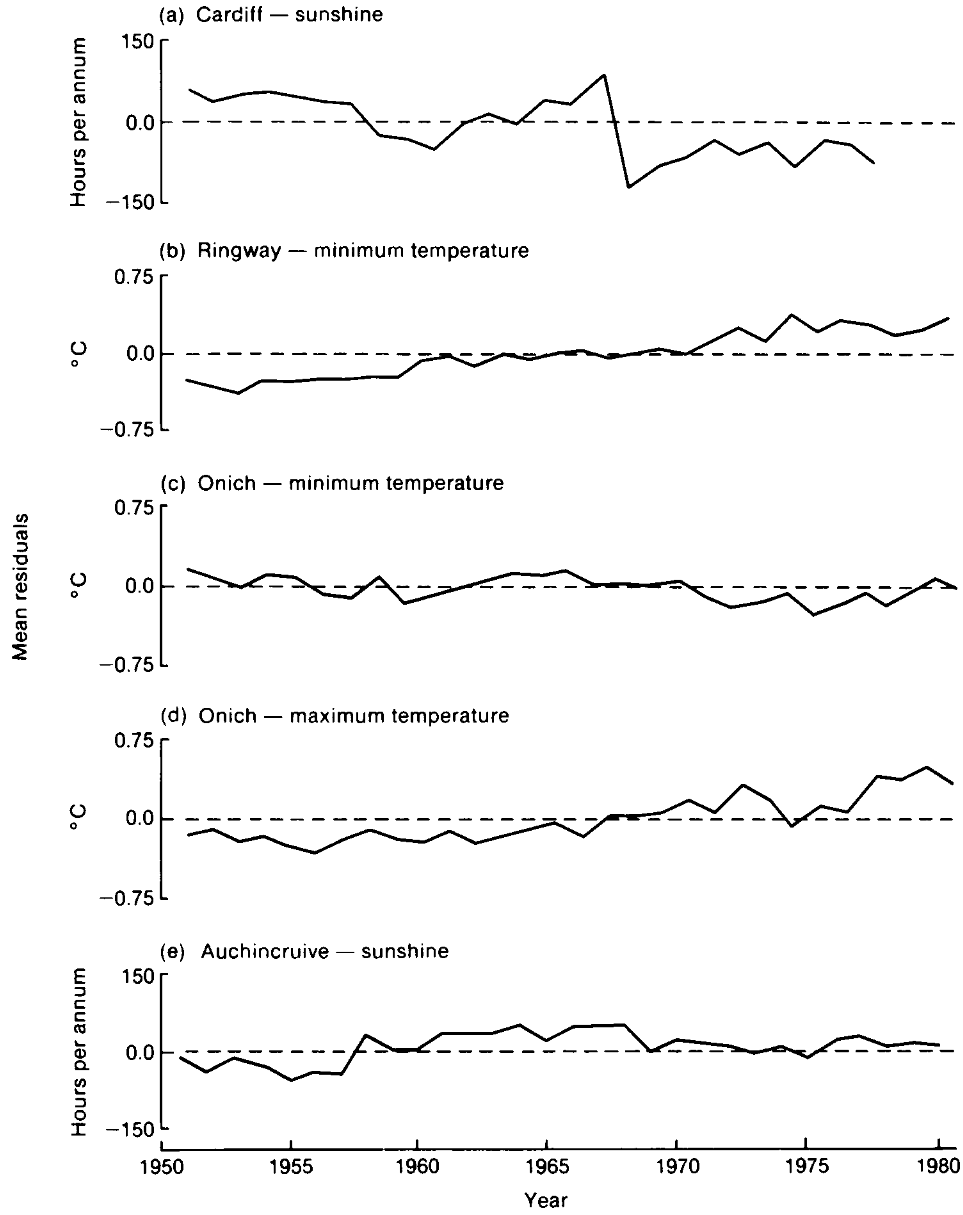

Figure 1. Annual mean residuals (observations minus estimates) for selected stations showing examples of inhomogeneities identified during the period 1951–80: (a) step inhomogeneity caused by change in site, (b), (c) and (d) changes in site exposure or character, and (e) deterioration of screen or instrument.

Figure 2. Annual mean residuals (observations minus estimates) for some of the Reference Climatological Stations listed in Table I showing inhomogeneities identified during the period 1951–80. The reference numbers (i)–(viii) refer to the possible causes of inhomogeneities listed in Table II. (The station at Cambridge is at the National Institute of Agricultural Botany (NIAB).)

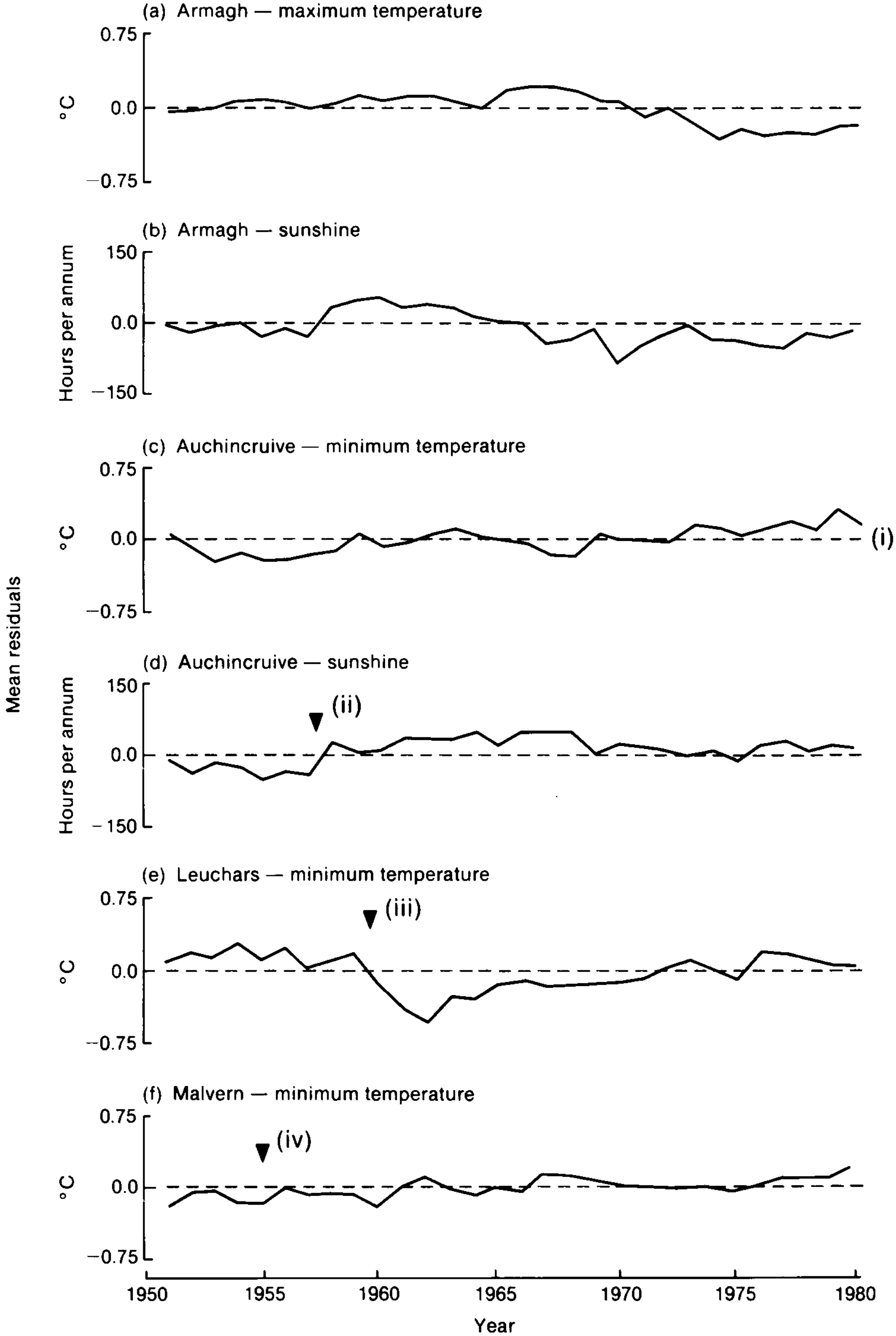
(a) Armagh — maximum temperature
0.75
°C
0.0
−0.75
(b) Armagh — sunshine
150
Hours per annum
0.0
−150
(c) Auchincruive — minimum temperature
0.75
°C
0.0
(i)
−0.75
Mean residuals
(d) Auchincruive — sunshine
150
(ii)
Hours per annum
0.0
−150
(e) Leuchars — minimum temperature
0.75
(iii)
°C
0.0
−0.75
(f) Malvern — minimum temperature
0.75
(iv)
°C
0.0
−0.75
1950
1955
1960
1965
1970
1975
1980
Year

Figure 2.

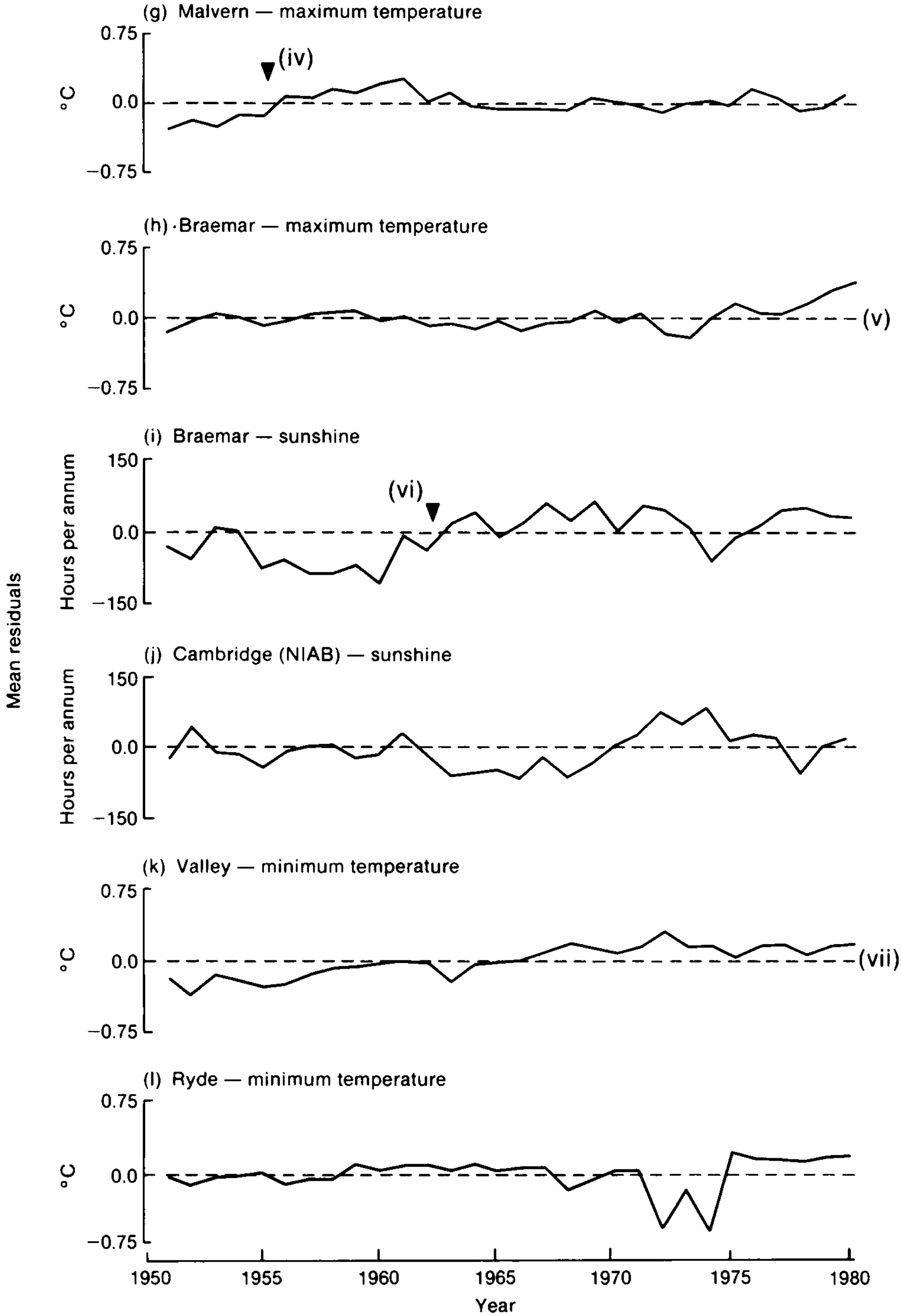

Figure 2 continued.

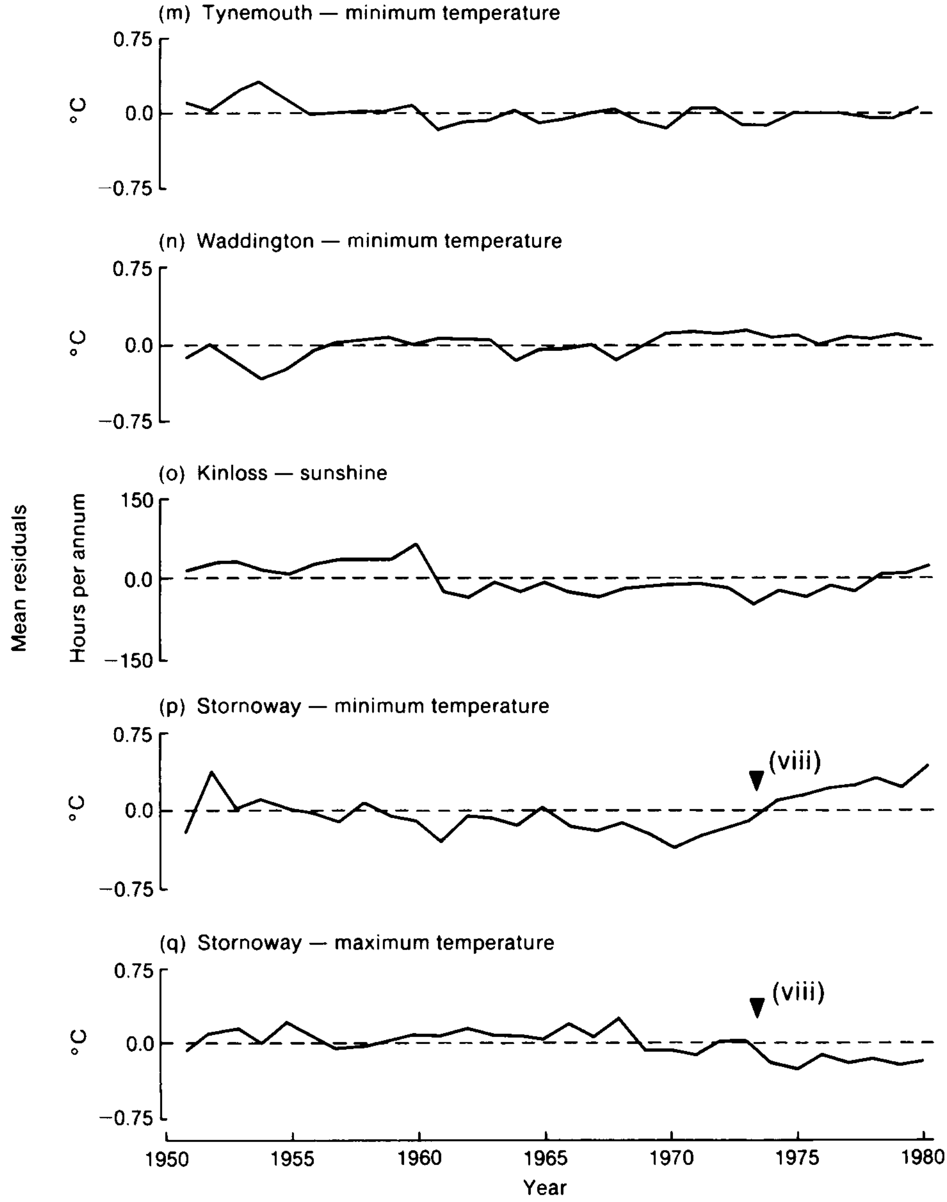

Figure 2 continued.

As a result, some level of inhomogeneity must be defined to be of practical as well as statistical significance. From an examination of the residuals it was decided that a level of ± 0.2 °C for temperature and ± 50 hours per annum for sunshine would be suitable.

Examples of inhomogeneities

Queries were raised for 34 stations (9%) for sunshine, 89 stations (15%) for maximum temperature and 116 stations (20%) for minimum temperature. From plots of the residuals it was apparent that the majority of inhomogeneities consisted of gradual changes in recorded temperatures and sunshine. The inhomogeneities may, however, have several causes:

(i) Step inhomogeneities caused by changes in site: observations of sunshine at Cardiff (Fig. 1(a)) clearly illustrate this feature. In 1960 the growth of trees at the initial site led to a decrease in observed sunshine of approximately 80 hours per annum. The recorder was moved and values returned to their previous levels. However, in 1967 the recorder was again moved, to Ty Twyn, a poor site obscured by trees. The level of sunshine recorded fell by approximately 150 hours per annum (25 minutes per day) until the station closed in 1976.

(ii) Changes in site exposure or character: for example, by the growth of trees or urbanization. Since most of the long-period stations are in urban sites it is important that the latter feature be identified. Fig. 1(b) illustrates the residuals for Ringway where increased urbanization has resulted in a gradual increase in minimum temperatures by 0.5 °C over the 30-year study period. Onich (Figs 1(c) and (d)) also exhibits the effects of changing site characteristics. Here, the growth of trees increased the shelter around the site and resulted in a gradual increase in the diurnal temperature range.

(iii) Deterioration of screen or instruments: a notable example of this is apparent in the residuals of sunshine at Auchincruive (Fig. 1(e)). An amber sphere, in use until 1957, was replaced and the residuals show a clear increase in the sunshine recorded.

(iv) Small changes in site and instrumentation, or varying accuracy between observers: these would usually result in very small changes which would not normally reach the 0.2 °C or 50 hours per annum thresholds. Occasionally, however, successive events may become significant.

In the 1951–80 study period, 231 (60%) of the 390 stations reporting all three elements were considered homogeneous. Of the 186 stations not reporting sunshine, 146 (78%) were deemed homogeneous for the temperature elements.

Homogeneity of the Reference Climatological Stations, 1951–80

The results previously illustrated indicate the problems associated with the identification of specific stations as Reference Climatological Stations. The requirement of a long homogeneous record is difficult to attain with small changes sometimes having a major effect on the observations recorded whilst major changes of site may have little effect. In addition, changes in site exposure, instrumentation and even observers have been shown to have some influence.

A list of the 21 reference stations selected in 1982 is provided in Table I together with the list of prospective stations suggested for future consideration. From an examination of the graphs produced it was apparent that ten of the current stations contained at least one inhomogeneity. Some of these could be considered negligible, but others showed clear discontinuities. One of the most notable was a site change in 1959 at Leuchars which adversely affected the minimum temperature record (Fig. 2(e)). However, a further site change in 1969 appeared to have little effect.

A complete list of the inhomogeneities identified within the 30-year period for both present and prospective reference stations is displayed in Fig. 2, with some possible causes postulated in Table II.

It is suggested that for the current reference stations flagged by the testing routine, several alternatives exist:

(i) To recognize that some may meet WMO Reference Climatological Station criteria for only one element.

(ii) To select a new reference station in the same area, for all elements.

(iii) To select a new reference station for the elements flagged as inhomogeneous.

(iv) To apply corrections, where possible, to the data series before any climatological study is undertaken.

Table I. *Reference Climatological Stations selected in 1982 (list (a)) together with prospective stations suggested for future consideration (list (b)). (Year of first observation at present site is given.)*

(a) Current

Aldergrove	1926	Leuchars	1921
Armagh	1851	Malvern	1890
Auchincruive	1932	Mount Batten	1920
Benbecula	1942	Ryde	1914
Braemar	1857	Squires Gate	1942
Cambridge	1950	Tynemouth	1914
Dale Fort	1950	Valley	1941
Eskdalemuir	1911	Waddington	1946
Falmouth	1869	Wick	1941
Ilfracombe	1912	Wye	1934
Lerwick	1921		

(b) Prospective

Aviemore	1982	Hurn	1951
Aughton	1978	Kinloss	1951
Boulmer	1975	Leeming	1965
Camborne	1978	Manston	1961
Elmdon	1949	St. Mawgan	1955
Exeter	1978	Stornoway	1942
Hemsby	1978	Tiree	1942
Herstmonceux	1978		

Site changes are clearly not the only influence on the climatological record of a station. A detailed examination of data records is needed to ascertain the homogeneity of any particular station series. 1950, however, there are insufficient data in machinable form to carry out this type of analysis.

Table II. *Possible causes of some of the inhomogeneities shown in Fig. 2*

Reference number	Cause
(i)	Thermometer changes throughout period
(ii)	Amber sunshine sphere replaced 1957
(iii)	Site change 1959
(iv)	Site change 1955
(v)	Thermometer changes throughout period (5 in 10 years)
(vi)	Site change 1963
(vii)	New site 1963, moved enclosure 1966
(viii)	Site change 1973

Implications for detecting climatic trends

What then should determine the choice of Reference Climatological Stations? Clearly the future continuation of a station must still be considered a major aspect in its selection but a knowledge of past fluctuations, not of climatic origin, is also necessary. It is apparent that a large percentage of the present reference stations, previously considered to contain long, homogeneous records of climatological observations, do in fact contain inhomogeneities.

The majority of inhomogeneities identified are not clear discontinuities caused by changes in site, but more gradual trends caused by changing site conditions and instrumentation. Although this study does not consider wind or rain, similar conclusions were reached by Tabony (1980) after studying rainfall data for the period 1911–70. He showed that trends ranged from −4.0 to +5.9% per decade, three times the range that might be expected by chance. These trends are difficult to correct but may become significant.

As a consequence, it is suggested that the use of single stations to monitor climatic change may result in the inclusion of unrepresentative trends and inhomogeneities. Two alternatives are suggested:

(i) The calculation of a regional series to monitor climatic trends: the use of several stations will reduce the impact of inhomogeneities in any one of the records. This is similar to the approach developed by Manley (1974) although the current high density of stations permits the nomination of smaller study regions.

(ii) A thorough investigation into the homogeneity of stations for different time-periods: this will assist in the construction of a composite series of data from sections of individual station records which have been shown to contain representative trends for specified periods of time.

This present work has been used to suggest suitable Reference Climatological Stations for the period 1951–80 for the variables studied and these are identified in Fig. 3. They include Malvern, homogeneous after 1955, and Edgbaston, which closed in 1979. Further investigations of other periods will be continued to assist in the selection of stations which can be used to monitor climatic change before 1951.

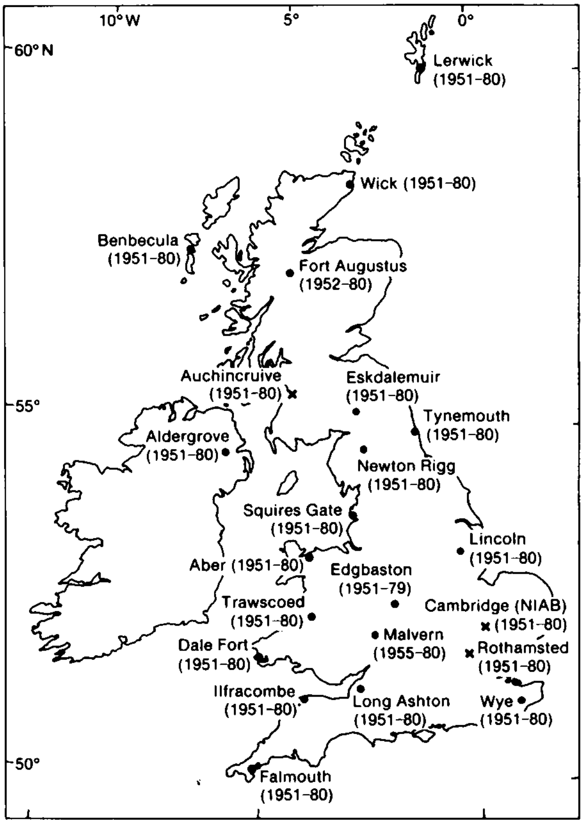

Figure 3. Suggested Reference Climatological Stations for the period 1951–80 suitable for minimum and maximum temperature and sunshine records (●) or temperature records only (X). (The station at Cambridge is at the National Institute of Agricultural Botany (NIAB).)

Conclusions

Of stations investigated for the 1951–80 period, 34% contained inhomogeneities. These included more than 45% of the reference stations currently being used to monitor climatic change. Several different types of inhomogeneity have been observed with the majority consisting of gradual trends in the values recorded. Corrections can be suggested for any clear step discontinuities caused by site changes but the gradual trends cannot easily be corrected.

Instead of using specific reference stations to monitor climatic change, it might be preferable, assuming a sufficiently dense station network, either to

(i) calculate regional series (the use of more than one station would reduce the dependence on any particular station which might contain inhomogeneities), or

(ii) set up a composite series of data based on sections of individual station records considered to contain representative trends for specific periods of time.

Suitable stations for the period 1951–80 are suggested and work is in progress to select representative stations for other periods. The implementation of the monitoring routine at regular intervals will help to ensure that stations selected for reference purposes continue to meet the criterion of the WMO.

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The Cyprus tornado of 29 May 1985

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Summary
A rare inland tornado in Cyprus is discussed.

1. Introduction

While winter waterspouts of varying intensity are not uncommon around the southern shores of Cyprus, some occasionally even crossing the coast, inland rotational phenomena on the island are rarely reported and appear in the main to be relatively minor events (McGinnigle 1970). However, the tornado which occurred between 1100 and 1200 GMT (1400–1500 Local Time) on 29 May 1985 in the Kornos/Pyrga area (see Fig. 1) was a frightening and destructive one. This article examines the event through observations, satellite pictures and eyewitness reports of damage.

2. Observations

Fig. 2 shows the 300 mb chart for 1200 GMT. The upper trough was moving slowly eastwards and, at the time of the tornado, was positioned just to the west of Cyprus. The progression of the trough over the past 48 hours is indicated on the chart. Tornadoes and waterspouts in the Cyprus area are often associated with such patterns and the present case is strikingly similar to that reported by Hardy (1971).

The infra-red satellite picture for 1055 GMT (Fig. 3) shows the convection associated with the upper trough and, of particular interest, the prominent cluster of convective cloud over the eastern part of Cyprus.

Although from the satellite picture the area of cloud appears widespread, there was nevertheless a strong orographic influence exerted by the Troodos Mountains. All the convective precipitation was confined to the east of Mount Olympus and north of a line from Mount Olympus to Larnaca (see surface

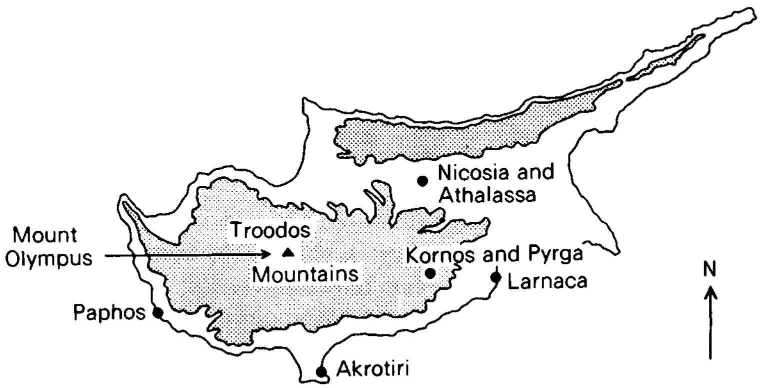


Figure 1. Map of Cyprus showing places mentioned in the text.

*Now at Royal Air Force Leuchars

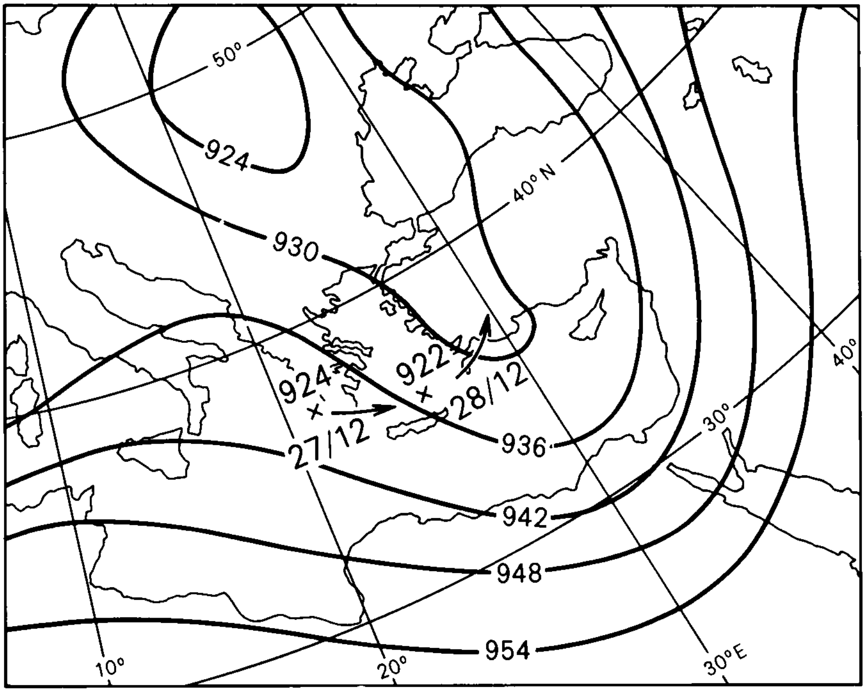


Figure 2. 300 mb chart for 1200 GMT on 29 May 1985. Crosses indicate estimated centres of low geopotential at 1200 GMT on 27 and 28 May. Heights are in decageopotential metres.

observations, Fig. 4). The long spell of thundery rain at Nicosia probably resulted from the interaction of the orographic influence of the mountains and the south-westerly upper winds. This is partially confirmed by cloud base reports of high- and medium-level cloud lowering towards the mountains throughout the period.

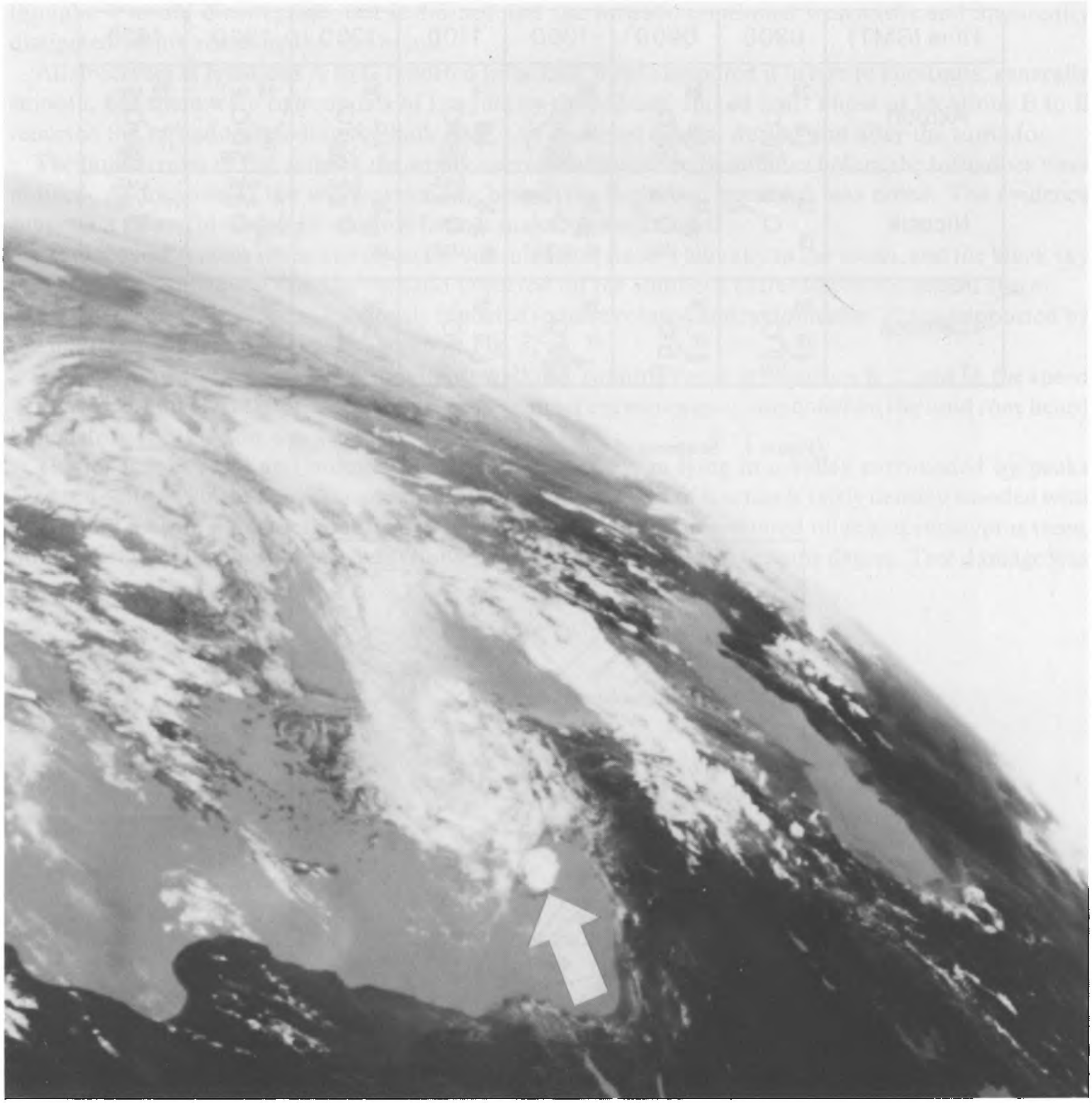
Unfortunately, lightning put the wind-finding radar at Athalassa out of action. However, the other sensors continued to function and the data are shown in Fig. 5. It is clear that, once the surface layer is lifted above 875 mb, the air is very unstable. This is consistent with the strong influence of the mountains discussed above. (The upper-level winds from the 0600 GMT ascent are also shown in Fig. 5.)

3. Eyewitness reports

Fig. 6 shows the probable path of the tornado (or tornadoes) based on eyewitness reports and a study of the damage. The following story emerges.

At about 1400 Local Time a lady at location A noticed a strong rotational whirl which swept through her apricot trees. At the same time a subdued roaring noise to the north (behind a nearby hill) passed from north-west to south-east. At about the same time observers at B saw three 'hooks' (presumably funnel clouds) developing downwards from the cloud base to the north, and tracking south-east towards Kornos. Two of these merged into one, and the remaining closely spaced pair eventually touched ground close to a house at C, and stripped off part of the roof. The inhabitant of the house saw only one tornado at this stage, and said that it was about 30 m wide. However, he was somewhat confused and frightened and quickly sought refuge indoors.

Eyewitnesses at D were adamant that two tornadoes, 'not very wide', passed one each side of the 364 m hill immediately to the south. Workmen laying a new road at E heard a roaring noise coming from the



Photograph by courtesy of European Space Agency

Figure 3. Infra-red satellite photograph for 1055 GMT on 29 May 1985. Arrow indicates the cluster of convective cloud over the eastern part of Cyprus.

direction of that hill, and saw just one tornado, approximately 100 m wide. It was at about this point that the electricity pylon (Fig. 7) was twisted and brought down, and a tractor was overturned, causing the only fatality. The tornado continued to approach the men at E and passed about 100 m to the south. According to people at F, it crossed Pyrga village and then curved sharply westwards, slightly north of its previous track. This brought it back directly over the new reinforced concrete and breeze-block building at E in which the workmen were sheltering. The building was so violently shaken that they

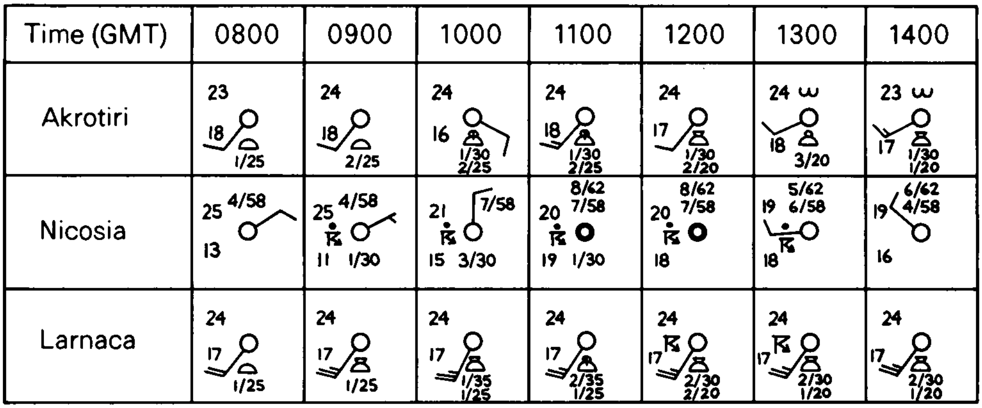


Figure 4. Sequence of surface observations for 29 May 1985.

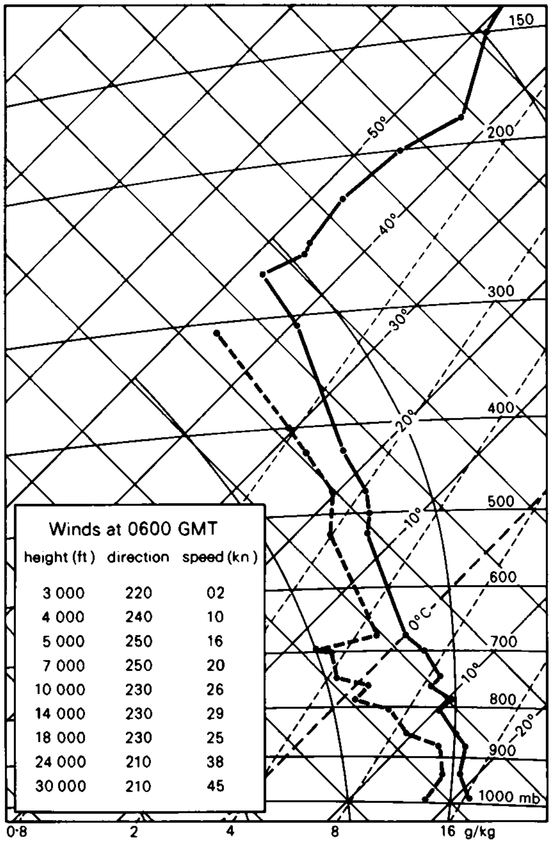


Figure 5. Upper-air ascent for Athalassa at 1200 GMT on 29 May 1985. Winds are for 0600 GMT on same day.

thought it would disintegrate, but it did not and the tornado continued westwards and apparently dissipated before reaching the 364 m hill.

All observers at locations A to G reported large hail; most compared it in size to chestnuts, generally smooth, but there were two reports of irregularly shaped and spiked hail. Those at locations B to E reported the tornado preceding the hail. At F hail occurred before, during and after the tornado.

The bold arrows in Fig. 6 mark the wind experienced for some 10 minutes before the tornadoes were noticed. At location G the wind prevailing before the large hail occurred was noted. The evidence suggests a powerful divergent outflow from a major downdraught.

Several eyewitnesses remarked upon the sunshine and watery blue sky to the south, and the black sky to the north, confirming that the tornado occurred on the southern extremity of the parent storm.

The tornado was almost unanimously reported to have rotated anticyclonically. This is supported by the nature of the tree damage, as shown in Fig. 8.

The tornadoes were reported as moving at walking/running speed at locations B, C and D, the speed of a car at E, and at walking pace again at F. Also most eyewitnesses commented on the loud roar heard long before the tornado was seen.

The locality is rural and mountainous, Kornos and Pyrga lying in a valley surrounded by peaks between 400 and 700 m above mean sea level. The area just east of Kornos is fairly densely wooded with young and mature pine trees, but further east it is more open with scattered olive and eucalyptus trees. Some 60 of the 110 mainly stone-built houses in Pyrga were damaged to some degree. Tree damage was

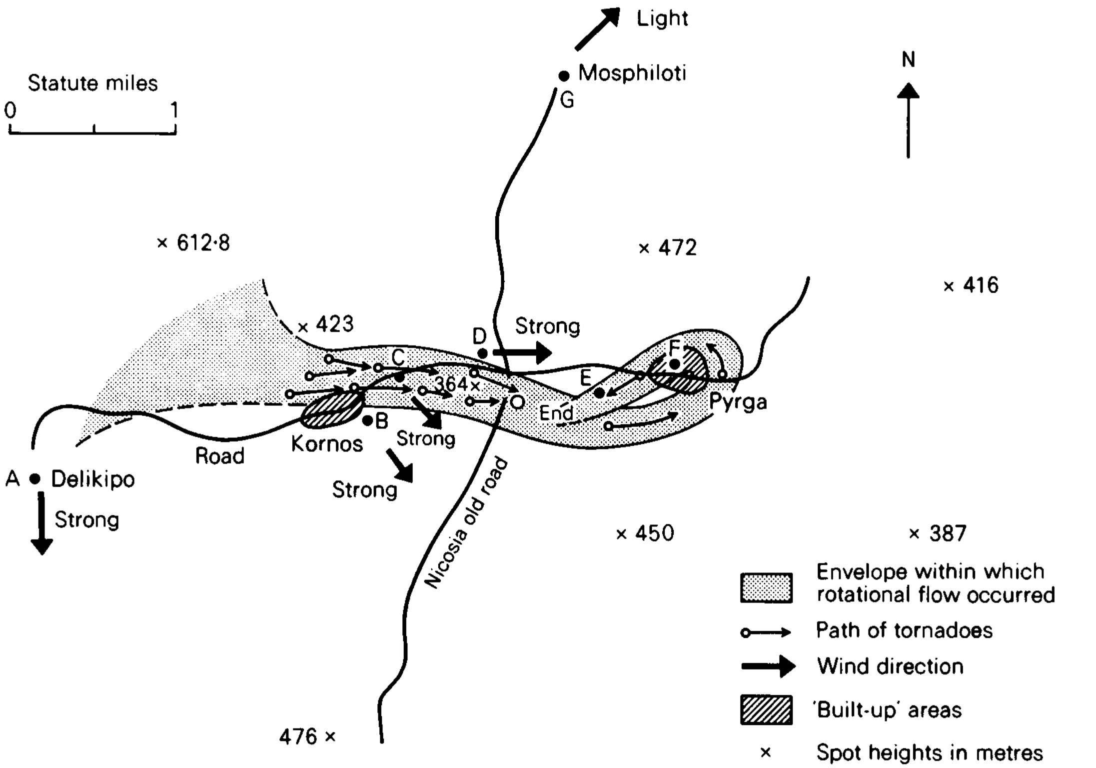


Figure 6. Sketch map showing probable path of the tornadoes based on eyewitness reports and reported damage.

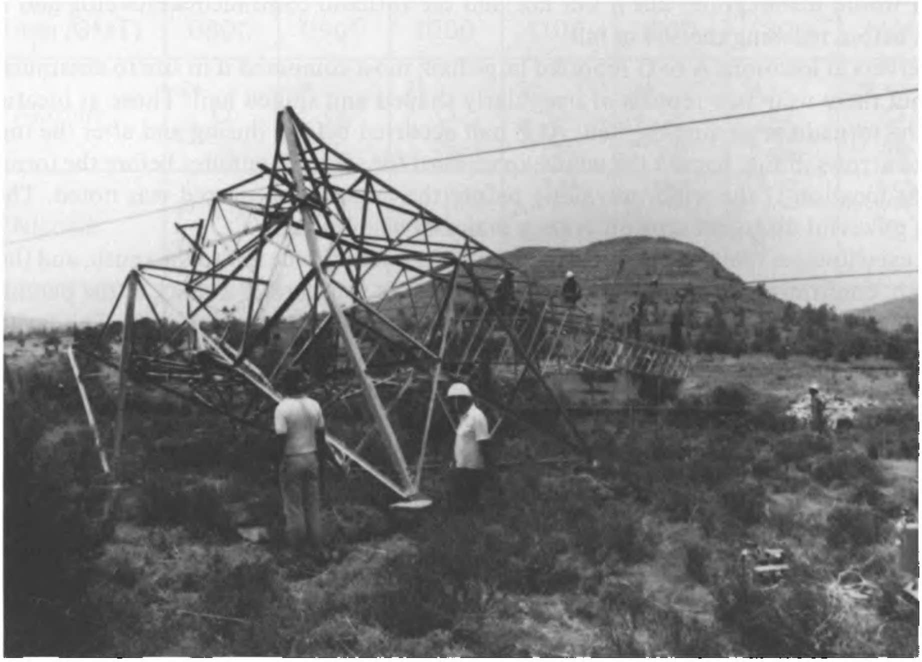


Figure 7. The electricity pylon near location E in Fig. 6.

Figure 8. Damaged pine tree near location D in Fig. 6.

extensive — scores of mature trees were uprooted but some, near the tornado touchdown area, were snapped or twisted off some 5 m above the ground.

4. Classification of the tornado

The structural damage, path length and path width suggest that the tornado should be classified as 1,2,2 on the Fujita–Pearson (FPP) scale (Fujita 1973); the evidence of structural damage was, however, confined to the time that the tornado passed over Pyrga. Alternatively, comparison of the rural damage with the categories of the TORRO scale (Elsom and Meaden 1984) would suggest force T4, denoting a severe tornado with wind speeds of 54–63 m s^{-1}. The description for the T4 category is 'large well-rooted trees uprooted, snapped or twisted apart'; the evidence for this clasification comes mainly from the area east of Kornos.

5. Conclusions

The severe local storm which shed this tornado occurred over the eastern part of the Troodos Mountains, a known preferred area for such storm development. Contributory factors were assessed to be:

(i) The upper trough which crossed Cyprus eastwards as a relaxing but well-marked feature.

(ii) The moist layer up to 880 mb, evident from the Athalassa radiosonde ascent, and from the coastal low-level cumulus. More usually the moist layer is capped by an inversion much nearer sea level.

(iii) The high value of wet-bulb potential temperature in the lowest 1000 m resulting from the upper trough overriding the lower levels (Carlson and Ludlam 1968). Note also the directional shear measured at Athalassa at 0600 GMT and shown in Fig. 2 for 1200 GMT.

(iv) The isolated trigger of intense local heating over the central massif of an island surrounded by relatively cool seas. This is to be coupled with the orographic effects generated as the low-level boundary-layer air was forced over the mountains.

There was little in the synoptic data to indicate that a severe storm would develop in the area. The strong surface wind at Larnaca is a characteristic event at this time of year, as is the high surface temperature and relative humidity. Perhaps the 300 m wind over the south-eastern part of the island was more veered than usual, but not sufficiently to arouse particular interest. The one indicator that may presage such events appears to be the presence of a plume of cirrus cloud spreading several hundred kilometres north-eastwards away from a 'hot-point' source. This is evident in the satellite picture of this event, the plume starting over Cyprus. However, convection must have already begun to form before such a signature becomes evident. Nevertheless, a combination of the characteristic upper-level contour pattern coupled with a close monitoring of the satellite pictures may give at least a few hours warning.

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ECMWF — ten years of European meteorological co-operation

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Summary

An account is given of the objectives of the Centre which was formally established in 1975, its organization and control by the various countries that support it (the Member States), the forecasting model and data-assimilation system, the computer system, the schedule of operational forecasts, and the way the forecast products are disseminated. There has been a steady increase in forecast skill over the past six years with a corresponding increase in use of the products by the Member States, and further progress is expected.

Background

The European Centre for Medium Range Weather Forecasts (ECMWF) was formally established on 1 November 1975, a date when its Convention had received sufficient ratification to come into force. However, as described by Knighting (1978), this followed a long period of careful planning and preparation which started as long ago as October 1967, when the council of Ministers of the European Communities adopted a resolution to promote a common program for scientific and technical research. The problem of extending useful weather prediction into the medium range was singled out as one of several projects where a joint European effort was regarded as essential, and where, according to different assessments, the benefit would by far outweigh the cost.

John von Neumann had already outlined an overall strategy in atmospheric modelling and prediction in 1955 (von Neumann 1960). He considered that the prediction problem could conveniently be divided into three categories depending on the time-scale of the forecast. In one category came short-range prediction of motions, determined mainly by the initial state of the atmosphere. The second comprised much longer-term prediction of characteristics of motion that are largely independent of the initial state, and thus include the problem of climate simulation. In between these two extremes there was another category for which it was necessary to consider the details of both the initial state and of external forcing. The logical approach was to attack these problems in that order.

In the early 1970s there was enough experience in both short-range prediction and climate simulation by numerical models to justify a serious attempt to tackle the medium-range forecast problem which falls into the third, and perhaps most difficult, of the categories listed above. In the planning documents leading up to the creation of the ECMWF, medium-range forecasting was considered to imply a period from four to ten days ahead, but a more natural time interval is perhaps two days to two weeks.

Medium-range forecasting was in many ways an ideal candidate for co-operation. The scientific and technical problems are formidable, and only very few countries have enough scientific and technical experts to tackle them. Moreover, the computer and other resources needed exceed those normally practicable at the national level. Medium-range forecasts are less time-critical than short-range ones, and there is little disadvantage from an operational point of view if they are made at a distance from the national forecast offices, on condition that fast and reliable telecommunication links exist.

The Centre's objectives and organization

It is convenient to recall the objectives of the Centre as laid down in its Convention. They are:

(i) To develop dynamic models of the atmosphere with a view to preparing medium-range weather forecasts by means of numerical methods.

(ii) To prepare, on a regular basis, the data necessary for the preparation of medium-range weather forecasts.

(iii) To carry out scientific and technical research directed towards improving the quality of these forecasts.

(iv) To collect and store appropriate meteorological data.

(v) To make available to the meteorological offices of the Member States in the most appropriate form, the results of the studies and research provided for in the first and third objectives above, and the data referred to in the second and fourth objectives.

(vi) To make available to the meteorological offices of the Member States for their research, priority being given to the field of numerical forecasting, a sufficient proportion of its computing capacity, such proportion being determined by the Council.

(vii) To assist in implementing the program of the World Meteorological Organization.

(viii) To assist in advanced training for the scientific staff of the meteorological offices of the Member States in the field of numerical weather forecasting.

The governing body of the ECMWF is a Council composed of not more than two delegates per Member State. The Council has three advisory bodies on financial, scientific and technical matters. The Council and its advisory bodies meet once or twice a year. The Centre is organized in three departments, and its director is appointed by the Council.

There are at present 17 Member States (see Table I) and, in addition, a special co-operation agreement

Table I. *Percentage budgetary contributions to the ECMWF for the period 1985–87*

Member States	Contribution %
Belgium	3.06
Denmark	1.82
Federal Republic of Germany	22.41
Spain	5.96
France	18.43
Greece	1.23
Ireland	0.53
Italy	11.33
Yugoslavia	2.16
Netherlands	4.64
Austria	2.17
Portugal	0.72
Switzerland	3.17
Finland	1.51
Sweden	3.44
Turkey	1.76
United Kingdom	15.66

has been signed with Iceland. The Centre is financed by contributions proportional to the Gross National Product of each Member State, a figure which is reviewed every third year. Member States' contributions for the year 1985 total £8 465 000, almost 95% of which goes on staff, computer equipment and associated expenditure.

The Centre's headquarters are in Shinfield Park, near Reading and about 15 kilometres from Bracknell. The building, covering more than 6000 square metres, and the land were provided by the United Kingdom, and occupied from 1979 (Wiin-Nielsen 1979), the same year that the Centre started to do operational forecasts.

The forecasting system

The Centre's forecasting system consists of two components: a general circulation type model and a comprehensive data-assimilation system. From the very start the Centre set out to develop a model which could describe the evolution of weather on all time-scales; in fact the same model (but with different horizontal resolution) has been used to predict intense small-scale weather phenomena (such as typhoons) as well as to simulate climate for periods of up to ten years. In the same way, the data-assimilation system was built in order to use not only conventional observations such as radiosonde data, but also asynoptic information from satellites and aircraft. The ECMWF data-assimilation system was successfully used to produce global analyses four times a day for the Global Weather Experiment. This data set, consisting of more than 70 000 global fields, has been used extensively by scientists all over the world.

The first numerical model used by the ECMWF was a grid-point model with 15 vertical levels and a horizontal resolution of 1.875 degrees of latitude and longitude. This model served for operational forecasting from September 1979 to April 1983. The finite-difference scheme conserved potential enstrophy during vorticity advection, a condition which is important when extending a prediction beyond several days. In April 1983 the grid-point model was replaced by a model using a spectral representation in the horizontal and a so-called triangular truncation at wave-number 63. The spectral technique was found to be more accurate than the grid-point model for the same computational cost. The number of vertical levels was increased to 16. Finally, in May 1985, a very-high-resolution spectral model was put into operation, whereby the spectral truncation was extended to wave-number 106. By and large this is equivalent to a grid-point model having a horizontal resolution of about 100 km.

Very substantial efforts have gone into developing a detailed description of the different physical processes which become more and more important as forecasts extend into the medium range.

The fundamental process driving the earth's atmosphere is heating by incoming short-wave solar radiation and cooling by long-wave radiation to space. The heating is strongest at tropical latitudes, while cooling predominates at polar latitudes, especially in the winter hemisphere. The bulk of the net incoming solar radiation is absorbed by the underlying surface rather than the atmosphere. However, evaporation of moisture and surface heating lead to much of this energy being transferred to the atmosphere as latent and, to a lesser extent, sensible heat. Thus the dominant direct heating of the atmosphere is found to be the latent heat released with deep tropical convection.

Radiative fluxes in the ECMWF model are calculated for five spectral intervals — two for solar and three for terrestrial radiation. The effects of water vapour, ozone, carbon dioxide and selected aerosols are included. The model predicts the cloud cover as a function of humidity, static stability and convective activity. The Centre's cloud scheme has gradually developed, and several Member States are using predicted clouds as a direct model output parameter. The prediction of boundary clouds and the outflow of cirrus from deep convective clusters were introduced in May 1985 with the new very-high-resolution spectral model.

The treatment of physical processes in the boundary layer deserves considerable attention in medium-range forecasting. The calculation of boundary-layer fluxes is based on the Monin–Obukhov similarity theory, which assumes that the gradients of wind and internal energy are universal functions of a stability parameter to be determined from empirical data. The roughness length over land depends on vegetation and sub-grid-scale orography. Over the sea the roughness length is given by the Charnock formula (Charnock 1955).

The model deals separately with deep and shallow convection. A correct handling of convection is essential, not only for tropical forecasting *per se* but also for the overall maintenance of the large-scale tropical circulation systems, which are important for the large-scale circulation at higher latitudes.

Medium-range weather prediction requires global observations of high quality, coverage and resolution. Thus a continued improvement in medium-range forecasts is strongly dependent on the Global Observing System. Good observations through the depth of the atmosphere over remote ocean areas are as important as good observations over land, so that observing systems providing a homogeneous data coverage for large areas are of particular importance.

For this reason the ECMWF has devoted considerable research efforts to develop a four-dimensional data-assimilation system in order to make efficient use of temperature and moisture soundings from the polar-orbiting satellites and to use wind observations from the geostationary satellite platforms.

The computer system

The ECMWF's first generation computer, installed in 1978, had a Cray 1-A mainframe, with a performance of about 100 MFLOPS (million floating-point instructions per second). This was replaced in 1983 by a Cray X-MP dual processor, which in turn was replaced at the end of 1985 by a four-processor version (the Cray X-MP/48). The throughput of the Cray X-MP/48 is about ten times that of the Cray 1-A.

The Cray X-MP is connected via a data link, the Loosely-Coupled Network. It is also directly coupled to two front-end processors, a Cyber 835 and a Cyber 855. A dedicated VAX 11/750 minicomputer takes care of graphical applications, and an IBM 4341, with an attached mass storage, is needed for archiving the Centre's data. In-house connection to the Cyber computers is via a Gandalf system, and external communication via an RC 8000. It is through this machine (to be replaced by a VAX-oriented system later this year) that the Centre acquires its observational data from the Global Telecommunication System (GTS), via links to the Regional Telecommunication Hubs at Bracknell and Offenbach, and transmits its analyses and forecasts to Member States. Details of the ECMWF computer system are shown in Table II.

Table II. *Details of the ECMWF computer system*

Computer	Memory	Disc or tape storage	
Cray X-MP/48	64 Mbytes 256 Mbytes (SSD)*	21 disc units	10.300 Gbytes
Cyber 835 Cyber 855	4 Mbytes 12 Mbytes	26 disc units 10 tape units	10.700 Gbytes
IBM 4341	8 Mbytes	10 disc units cartridge tapes 6 tape units	12.500 Gbytes 105.000 Gbytes
4 × VAX 11/750	18 Mbytes each	7 disc units 1 tape unit	2.100 Gbytes
2 × RC 8000	576 Kbytes each	1 tape unit 2 disc units	0.132 Gbytes

* Solid-state storage device

Production and dissemination of forecasts

On its general operational schedule, the ECMWF makes one forecast each day for ten days ahead, starting from the 1200 GMT analysis. No other operational forecast is currently run. At about 1700 GMT each day an analysis valid for 1800 GMT the previous day is carried out, thus providing the first guess for the 0000 GMT analysis which is carried out at about 1800 GMT each day. Similarly, analyses for 0600 and 1200 GMT are carried out at around 1830 and 2000 GMT, the final analysis having a data cut-off time of about eight hours. It is from this that the ten-day forecast is run.

Forecasts are distributed to the Member States in digital form. The present distribution amounts to over 10 000 products each day from the Centre. A product is defined as one parameter (e.g. geopotential) for one level (e.g. 500 hPa) for one time-step (e.g. forecast time 240 hours) for one area (e.g. a European area). A selection of ECMWF products is distributed daily to users all over the world via the GTS (Table III).

Table III. *A selection of ECMWF products disseminated on the Global Telecommunication System*

Product	Northern hemisphere (from latitude 20°)	Tropics (35° N to 30° S)	Southern hemisphere (from latitude 20°)
Mean-sea-level pressure	Analysis to day 6	—	Analysis to day 5
500 hPa geopotential	Analysis to day 6	—	Analysis to day 5
850 hPa temperature	Analysis to day 6	—	Analysis to day 5
850 hPa wind	—	Analysis to day 3	—
200 hPa wind	—	Analysis to day 3	—

Results of operational forecasts

Since the Centre started operational forecasting in September 1979 there has been a considerable improvement in the quality of the forecasts. This has been confirmed by both objective assessment and by subjective evaluation by users in Member States and elsewhere. The intercomparison study undertaken by the Commission for Atmospheric Science (Lange and Hellsten 1984) clearly demonstrated this, also that the Centre's forecasts were the most accurate among those participating in the intercomparison.

The improvements are due to continual development of the forecasting procedure, including both the model and the data-assimilation system. The greatest change to the model took place in May 1985; the effect of that change has led to a further significant improvement in predictive skill as can be seen from Fig. 1.

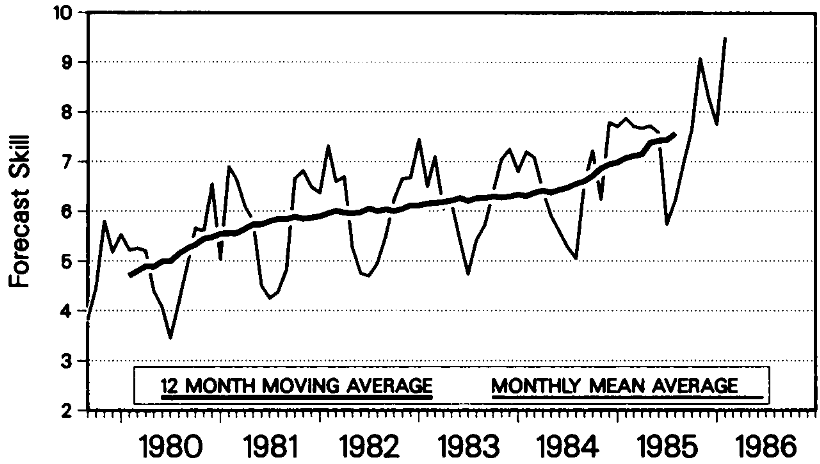

Figure 1. ECMWF forecast skill between September 1979 and February 1986. Forecast skill is based on 'days of predictability' derived locally at ECMWF.

Similar improvements have taken place in respect of forecasts for the southern hemisphere and the tropics, but from a much lower starting point. While the limit for useful forecasts for the northern hemisphere is six to seven days, corresponding values are four to five days for the southern hemisphere and three days for the tropics.

Usage of forecasts in Member States

While the operational forecast is being produced on the Centre's computer system, forecast products in the form of coded fields are being disseminated via dedicated telecommunication lines to the computer systems of the 17 Member States which support the ECMWF. The medium-range products have now become an integral part of the prediction routine in European forecast offices. Member States use the Centre's forecasts not only as an additional reference source, but also often as part of objective (statistical) interpretation schemes, as boundary values for their own limited-area models, or to drive other models (for example, sea and swell models for use in ship routeing). The primary end users of the medium-range forecasts interpreted by Meteorological Services of Member States are in the sectors of agriculture, marine, construction and heavy engineering, energy planning, leisure and tourism, land transport, environment and pollution (see Fig. 2).

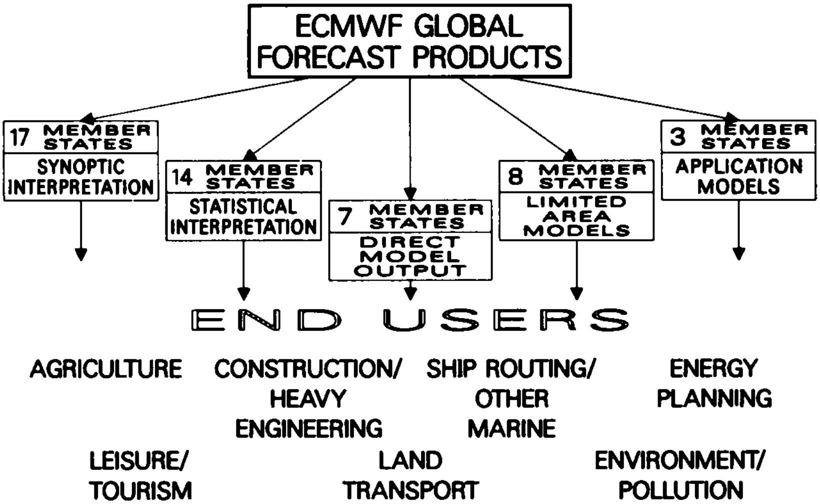

Figure 2. Application and use of ECMWF products in the Member States.

As well as standard operational products, the Centre's forecasting system also produces a range of products which are experimental in nature, such as cloud amounts, winds interpolated to the 10-metre level above the model surface, temperatures interpolated to the 2-metre level, fields smoothed by filtering to remove small-scale features (which cannot be well predicted at the later stages of the forecasts), time-averaged fields, and so forth. These additional products are also made available to Member States, and may be presented directly to forecasters or used in other ways (for example, as input parameters to statistical forecasting schemes). Thus, the Centre is assisting its Member States to improve the 'user interface' between numerically produced fields and the requirements for forecasts of actual weather elements by the end users of the forecasts.

Other services

Twenty-five per cent of the Cray computer resources and ten per cent of the Cyber resources are available for use by Member States. Computer time is distributed among the countries according to a special formula and is only partly proportional to the Gross National Product. Ten per cent of the time allotted to Member States is available for special research projects. Scientists may forward requests for this through any Member State.

The Centre is gradually building up an archive of raw and processed data (global analyses and forecasts). A special data set including selected basic observations and global analyses for seven standard levels has been developed covering a period of five years. The World Meteorological Organization (WMO) has contributed financially to the development of the data set which is currently being sent to a large number of users all over the world. The Centre is also in the process of re-analysing the Global Weather Experiment data using the most recent version of its data-assimilation system. As the Centre's archives are gradually developed, their value for the scientific community will increase more and more.

The Centre provides a two-month training course every year in advanced numerical weather prediction. The course is also open to scientists from non-Member States, 16 of whom participated over the past two years.

The Centre also gives an annual scientific seminar and organizes workshops in different subjects.

Future plans

Predictability studies recently carried out by Lorenz (1982) have indicated that the limit of predictive skill can be extended by between two and four days just by model improvements alone. Further amelioration of approximately two days can be expected due to the positive feedback of the model from the data assimilation. The Centre will maintain its successful 'brute force' strategy by continued enhancements to the complete forecasting system. Major problems are related to the treatment of orography, the parametrization of the boundary layer, and of deep and shallow convection. Continued progress in the performance of supercomputers will probably make it possible to run a global model with a resolution around 50 km before the end of this decade.

The quality of the Global Observing System is crucial for medium-range prediction. In a project supported by WMO, the Centre has recently developed a system for monitoring it. By intercomparisons of very-short-range forecasts (first guess to the analyses) with specific observations over periods of a month or so, systematic errors can be identified in the observations. Several cases of radiosonde observations with large systematic errors have been identified and the operators informed so that corrective action can be taken. It is believed that by instituting systematic quality control of observations with feedback to the producers, we shall achieve better-quality observations and consequently better forecasts.

This article is a revised version of the one that appeared in the *WMO Bulletin* for October 1985 and is published by permission of the Director of ECMWF.

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Reviews

Safety of dams: flood and earthquake criteria, by the Committee on Safety Criteria for Dams, the Water Science and Technology Board, the Commission on Engineering and Technical Systems, and the Natural Research Council. 150 mm × 227 mm, pp. xvi + 276, *illus*. National Academy Press, Washington, 1985. Price £18.50.

The safety of dams, particularly that of existing dams, presents major policy problems. Many existing dams do not meet current safety criteria whilst the consequences of their failure can be catastrophic. The US Natural Research Council were therefore asked by the United States Department of the Interior to prepare an inventory of currently used safety criteria for dams in respect of extreme floods and earthquakes, and to evaluate alternative criteria for the safety of Federal dams. The resultant report is thorough but is limited both in that the question they were asked to address is not a very useful one, and by the very limited time, seven months, they were given to answer it.

Given these constraints, the Report has focused on the choice of the design-magnitude events as criteria — the extreme flood event for spillway design, and earthquake magnitude for seismic safety. Unlike other fields of engineering, such as the nuclear and chemical industries, the design safety objective for major dams is that they should not fail under any foreseeable event, although a less stringent criterion may be appropriate for dams presenting a less serious hazard. The discussion in the Report on design criteria for flood events therefore revolves around the estimation of the Probable Maximum Flood. The Report recommends the continued use of this method as a criterion, but also states that less strict criteria may be appropriate both to existing dams and to dams presenting a minor hazard.

To this reviewer, these conclusions are not terribly useful, particularly in regard to safety criteria for existing dams. Currently dams are, as the Report notes, categorized in terms of a 'hazard classification'. This classification is based upon the potential energy stored and the nature of the downstream developments at risk. If the application of less rigorous criteria is acceptable for existing dams and for minor dams, then it seems reasonable to base these upon a rigorous analysis of the potential consequences of failure. However, the existing system seems crude; it does not include, for example, the time before peak for flood events. The longer this lead time, then the greater the opportunity to ameliorate the consequences of a failure. Similarly, very cursory consideration is given to the mode and speed of dam failure: this can vary greatly according to the type of dam. Equally, the Committee draws attention to the problem of classifying a dam in terms of the potential hazard it represents when, in the future, development may take place downstream. However, it fails to note that some flood protection dams, notably those on the Ganges system, are intended specifically to permit the intensification of use of the flood plain.

The Committee reports that some of its members would have wished to have attempted to formulate a hazard classification standard, but that they did not have time to do so. Seven months is obviously an inadequate time for a Committee to carry out such a task. However, given the coarseness of the existing hazard classification and the large number of existing dams which do not meet current criteria, a refined classification system is needed as a basis on which to decide when to relax current criteria. More especially it is needed to determine which dams should be given priority for remedial works. Such a classification would also be useful where the inadequacies of an existing dam arise, not from inadequate spillway capacity or seismic resistance, but for other reasons. It would therefore have been more useful to have asked the Natural Research Council to address this issue, and to have given them adequate time to do so, than to consider design criteria events. The difficulty in deriving such a hazard classification is that such generalized predictions as to the likely consequences of a failure are best derived from very detailed analysis of the consequences of the failure of specific dams.

Within the restrictions given to the Council, the Report makes a number of good points. Some of the discussion of economic issues is, however, ambiguous; the measurement of damages in terms of compensation being an example. Although the Report recommends that, in any benefit–cost analysis of dam safety, the potential loss of life should not be evaluated in money terms, it does note that capitalized values for lives lost have been so used. This approach is now regarded in the United Kingdom as being theoretically unsound.

C. Green

Climatic hazards in Scotland: Proceedings of the Joint Royal Scottish Geographical Society and Royal Meteorological Society Symposium, University of Stirling, June 1984, edited by S. John Harrison. 153 mm × 212 mm, pp. ix + 81, *illus.* Geo Books, Norwich, 1985. Price £8.00, US $14.00.

This small 81 page book details the proceedings of a joint Royal Scottish Geographical Society and Royal Meteorological Society Symposium held at the University of Stirling. As only nine papers are involved I will briefly attempt to describe each in turn.

A.H. Perry from the Department of Geography, University College of Swansea, opens the proceedings with a professional view of climatic hazards and their status in the hazard spectrum. This is followed by a conventional discussion of meteorological parameters and the hazards they can cause. Section three discusses in some detail extreme rainfall events and the Meteorological Office's apparent inability to forecast them. The fourth paper deals with floods as a hazard. The fifth contribution discusses the effect of wind on commercial forestry. It was this and subsequent papers that I found the most interesting. K.F. Miller described how the rate of attrition (measured in square centimetres per day) of unhemmed cotton flags provides a cheap and reliable guide to tree growth potential in relation to site exposure. It is thought that the rate of attrition of these cotton flags is determined largely by wind speed and wind gustiness. In his paper K. Smith, from the Geography Department at the University of Strathclyde, uses press reports to assess climatic hazards. He points out that while climatic extremes can occur anywhere, climatic hazards only happen where man and his works get in the way of these extremes. How better to assess man's perception of climatic hazards than to analyse press reports of weather-related events for a major conurbation, in this case Glasgow. In the seventh paper G. Edmond, from the Department of Roads and Transport, Highland Regional Council, looks at the problems associated with road maintenance and snow clearance in the Scottish Highlands. He states, 'although Meteorological Office forecasting has reached a considerable degree of accuracy, there is still a fair amount of forecasting of icy conditions which do not materialize'. He goes on to describe how ice detection systems could be a cost-effective solution to the problem of unnecessary salting. A representative from the insurance industry discusses, in chapter eight, the insurance aspects of extreme weather events. The general tenor of his article can be summed up with the quote, 'What has to happen for an event to qualify as extreme is perhaps debatable, but whatever the definition, they are occurring far too often and much more frequently than they did two or three decades ago'. S.J. Harrison in the final paper attempts to draw together many of the points raised and, considering the diversity of approaches, this was not an easy task.

I hope the above résumé gives some indication of the diversity of the papers presented at this meeting. Indeed it is the variety of opinion, approach and perception that makes this book readable. I feel the organizers have succeeded in their attempt to draw together those people whose work brings them into direct contact with the hazardous aspects of climate, and the resultant flow of ideas across disciplinary boundaries will, I hope, produce some answers to the many questions that this Symposium raised.

W.H. Moores

Tornado! Proceedings of the first conference on tornadoes, waterspouts, wind-devils, and severe storm phenomena, Oxford Polytechnic 29 June 1985, edited by G.T. Meaden and D.M. Elsom. 145 mm × 210 mm, pp. 72, *illus*. Artetech Publishing Company, Bradford-on-Avon, 1985. Price £10.00 hardback (£3.00 paperback).

These conference proceedings are published under the sponsorship of the Tornado and Storm Research Organization (TORRO) founded by Dr Meaden in 1974 as 'a privately-supported research body, serving the national public interest'. It publishes its findings mainly in *The Journal of Meteorology* (not to be confused with the defunct American publication of the same title) and subscribers will have received these proceedings as its 100th issue.

After a message of welcome from Professor H.H. Lamb, the work of the various divisions of TORRO is explained and papers are presented by the leading researchers. The divisions are: tornadoes (M.W. Rowe and G.T. Meaden), thunderstorms (K.O. Mortimore), hailstorms (D.M. Elsom), ball lightning (M. Stenhoff), and weather disasters (A. Thomas). There is also an article on building damage caused by tornadoes by P.S.J. Buller. The only Meteorological Office contributor is R.J. Pritchard of the London Weather Centre on 'The spatial and temporal distribution of British thunderstorms'. There then follows a number of case studies of recent tornadic phenomena and a joint statement from the TORRO directors on 'The tornado threat in Europe'.

There is little sign here of unscientific jumping to the wrong conclusions, though perhaps the Wiltshire whirlwind watchers may care to investigate the effect of a military helicopter hovering low over a cereal field. The professional meteorologist can only be amazed and impressed by the wealth of data on British severe storm phenomena accumulated by amateur and university enthusiasts and described here. It would be wrong to ignore their challenge to 'responsible authorities' to 'include tornado forecasting as part of national meteorological services, and issue tornado warnings on occasions of possible severe tornadoes'. TORRO has shown us that tornadic damage is more common in England than was thought a few years ago, but we must not assume that as much effort is needed to combat the threat by issuing warnings as in the USA. It is instructive to compare these proceedings with those of the 14th conference on severe local storms, published by the American Meteorological Society in 1985, where the 113 papers, many on radar, satellite and computer studies, indicate the amount of money being spent over there.

Has the Meteorological Office a role in combining the findings of the Americans, from R.C. Miller onwards, with the British data being collected by TORRO? We have good numerical models, a dense land surface observing network, and now radar, satellite and accurate SFERIC data. There would be a market in continental Europe as well as in Britain for more-detailed severe weather warnings.

K. Grant

Photograph by courtesy of Captain G.V. Mackie

The current and two former Presidents of the North Atlantic Ocean Stations Board (NOAS), photographed after the ceremony at Hull on 18 December 1985 when the Dutch vessesl *Cumulus* was handed over by the Netherlands Secretary of Transport and Public Works to the Parliamentary Under-Secretary of State for Defence Procurement for a nominal sum of £1.

From left to right, with terms of office in brackets, are: Dr Udo Gärtner (Federal Republic of Germany) (1986), Dr D.N. Axford (United Kingdom) (1982–85) and Mr Bert Kamp (Netherlands) (1978–81).

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