THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S
STATIONERY
OFFICE

August 1986

Met.O.971 No. 1369 Vol. 115

METEOROLOGICAL OFFICE Met.O.971

THE METEOROLOGICAL MAGAZINE

No. 1369, August 1986, Vol. 115

551.501.45:551.521.11:551.524.36

A comparison of the principal component and near neighbour methods for the areal quality control of minimum temperature and sunshine duration

By R.C. Tabony*

(Meteorological Office, Bracknell)

Summary

The principal component approach currently used for the areal quality control of temperature and sunshine is investigated with a view to optimizing the implementation of the technique. A near neighbour scheme was used as a benchmark against which the performance of principal components might be assessed. It was found that each approach provided a similar standard of quality control and that the implementation of the principal component technique was close to being optimal. The potential of the principal component method to obtain improved results was impaired by its tendency to fit errors and its inability to cope with skewed distributions. Nevertheless it gained over near neighbours as the data became less well correlated, and hence was able to produce better estimates at the more isolated stations. The adverse effects of a non-normal distribution also degraded the near neighbour scheme by reducing the efficiency of its flagging routines. The latter approach, however, was found to perform better for new stations for which pre-calculated components were not available.

1. Introduction

The climatological data banks held by the Meteorological Office on both paper and computer media form the only sources of information available to answer thousands of enquiries per year. The integrity of these data is therefore of prime concern to all and depends mainly on the standards of quality control maintained by a suite of programs based on consistency checks in time, space, and between elements. This paper is mainly concerned with the methods used to operate spatial consistency checks, especially those relating to daily observations of minimum temperature and sunshine. For wind and rain sophisticated near neighbour techniques are well established whereas for temperature and sunshine a simple near neighbour approach (Bryant 1979) was replaced by a principal component method (Spackman and Singleton 1982). In making this innovation a number of arbitrary decisions were made and a major aim of this work is to explore the scope for optimization of this new approach. A sophisticated near neighbour scheme was used as a benchmark against which the performance of the principal component technique might be assessed. The discussion is restricted to the use of the conventional station network although it is recognized that remote sensing may have a future role to play. A fuller account of the work described in this paper is provided by Tabony (1985).

* Now at Meteorological Office, Edinburgh.

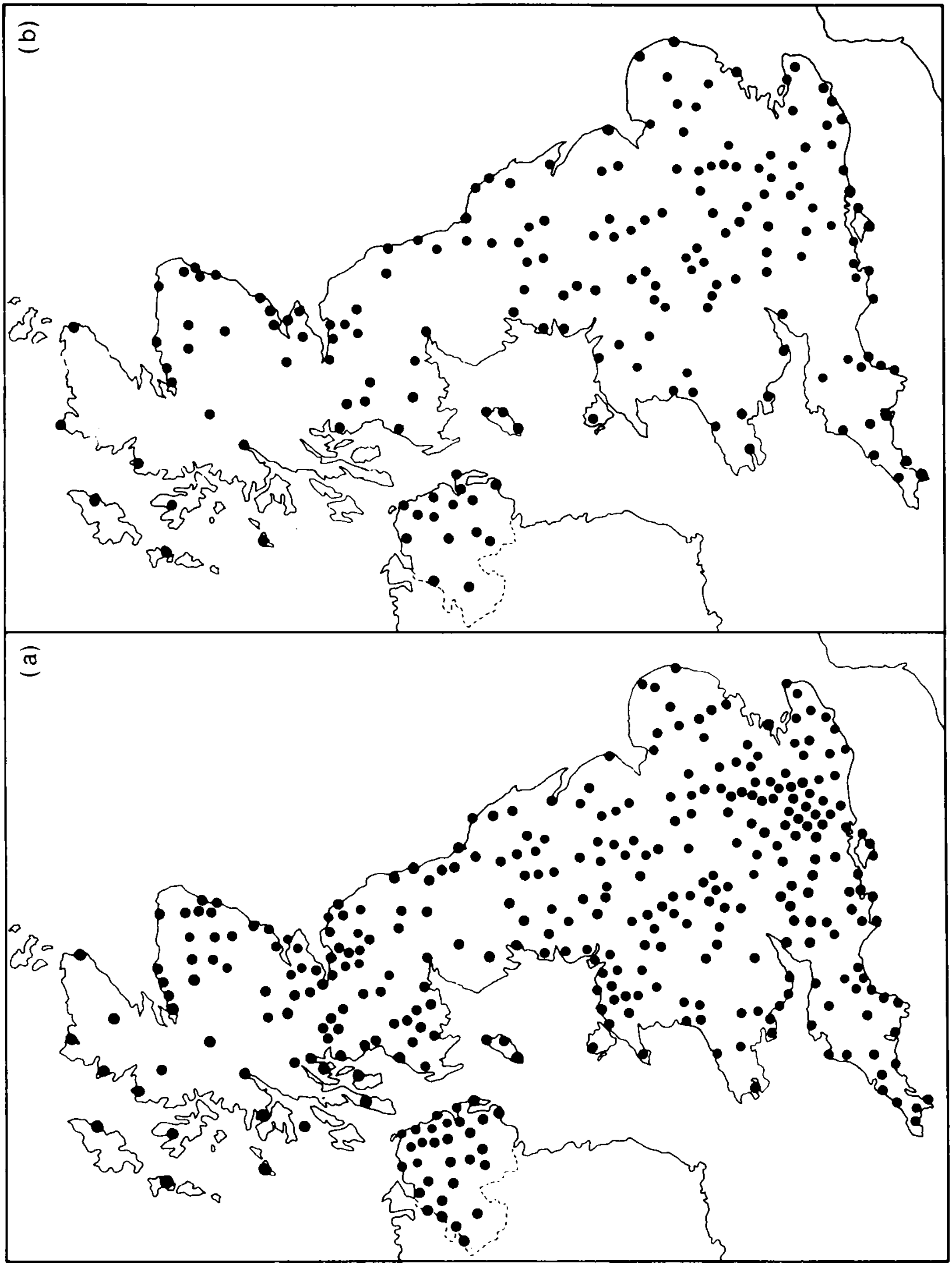


Figure 1. Distribution of stations for (a) minimum temperature and (b) sunshine.

2. Tbe data used and some of their characteristics

Data were extracted from every day during the period 1979–83 for sunshine and every third day for the period 1973–82 for minimum temperature. The persistence of temperature made it unnecessary to use data from every day in order to obtain near maximum information from the data set. The stations used were limited to those with 90% of data available in the periods considered, with the remaining values estimated as having the same temperature anomaly or percentage of average sunshine as that obtained from the mean of half a dozen or so neighbouring stations. This reduced the number of stations considered to 373 for temperature and 197 for sunshine, about one half to two thirds of the full network, and their distributions are shown in Fig. 1.

One of the most important criteria for the success of spatial quality control is the degree of correlation amongst the station network. In the present application the highest inter-station correlations average 0.92 for both elements considered, but the correlation decay is more rapid for sunshine than temperature (Hopkins 1977). This is reflected in the fact that for eighth-ranked neighbours, the correlation has fallen only to 0.87 for minimum temperature but to 0.80 for sunshine.

Another distinction between temperature and sunshine is that while the distribution of temperature is reasonably normal, that for sunshine is markedly non-normal, displaying U-shaped characteristics. This is likely to pose problems for all techniques based on the assumption of linearity.

3. The distribution of errors

In order to assess the performance of a quality-control system it is necessary to test it on data which have been contaminated with a realistic distribution of errors. A guide to these was obtained by examining the amendments made by the quality-control staff to the climatological returns for 50 to 100 stations in England and Wales during 1982–83. Errors of less than 2 °C or 2 hours of sun were ignored and only amendments ascribed by the writer to areal quality control were considered. This procedure led to error frequencies of 1 in 100 for minimum temperature and 1 in 190 for sunshine. The magnitude of sunshine errors varied seasonally in proportion to the maximum possible amount of sun, while those for temperature showed little seasonal variation. The annual distributions of temperature and sunshine errors are illustrated in Fig. 2, along with a fitted gamma distribution for temperature and a truncated normal distribution for sunshine which were used to represent the errors. The temperature and sunshine data under analysis were then contaminated with the appropriate distribution of errors.

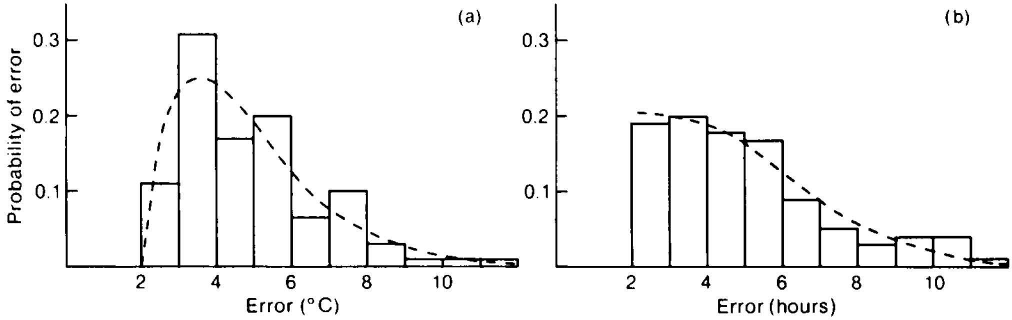


Figure 2. Histograms of errors identified by spatial consistency checks together with fitted distributions (dashed line) for (a) minimum temperature and (b) daily sunshine.

4. Comparison of principal component and near neighbour techniques

Principal component analysis enables fields of correlated data to be adequately represented by a small number of orthogonal patterns (components) in which each component explains the greatest fraction of the remaining variance. Its mathematical aspects are described in standard statistical texts (e.g. Kendall 1980) while a more discursive account is provided by Johnston (1980). Principal component analysis is now a very popular tool in meteorology and has two main uses — data reduction and data exploration, in which the rotation of the components to aid interpretation has been widely practised and discussed (e.g. Richman 1986). Quality-control applications are essentially concerned with data reduction, however, and so rotation of the components is unnecessary.

The principal component and near neighbour techniques both use relationships apparent during a past period of data to estimate observations at a station from neighbouring observations. In the near neighbour technique, only a single regression equation is available for making estimates on each and every day. In the principal component approach, each component can be regarded as a series of regression relations between stations whose weighting will vary from one day to another. The observations on a given day can then be reproduced by a linear combination of the regressions represented by the components.

If the data are very highly correlated then the near neighbour scheme should work reasonably well. Minimum temperatures at neighbouring stations with similar site characteristics, for instance, might be satisfactorily estimated by assuming a constant difference between the two. It is evident, however, that the principal component technique gains over near neighbours as the data becomes less well correlated. If the comparison were between minimum temperatures at a frost hollow and a standard site, for instance, then the differences between the two would be much smaller on cloudy than on clear nights. A 'constant difference' assumption would then be unsatisfactory whereas the principal component technique would be able to invoke different sets of regressions on clear and cloudy nights.

The advantage afforded to the principal component technique by its multi-regression approach is lessened if the input data are skewed. In these circumstances the physically based relations between stations will be non-linear whereas the regressions represented by the principal components are constrained to be linear. This disadvantage could be overcome by normalizing the data beforehand but this is not always easy. For sunshine, for instance, the skewness can act in opposite senses on different days, while for rainfall nothing can be done about that part of the skewness which is due to the large number of dry days.

The advantages which principal components may possess over near neighbours when operating on 'clean' data are also lessened when the test data contain errors, as will be the case for quality-control applications. The reason for this is that the principal component technique tends to fit errors, whereas the near neighbour approach does not. In the principal component method, the pattern of observations on a given day is matched against the patterns represented by the components. The presence of errors may cause some mismatching, but this is unlikely to be serious for the leading components. Thus mistakes in only 1% of observations are unlikely to upset estimates of north–south or east–west gradients across the country. The probability of a mismatch is much greater for the higher-order components, for which the number of stations contributing substantially to the pattern is much smaller. If a component was determined largely by the behaviour of only ten stations, for example, then an error in an observation at one of the stations would seriously upset the weighting to be attached to that component.

5. Estimation by principal components

The accuracy of the estimates is assessed by calculating the root-mean-square (r.m.s.) value of the residuals between the estimates and the true observations. The tendency of the principal component technique to fit errors means that the residuals on occasions of erroneous observations will be larger than those associated with correct observations, and a distinction must be drawn between the two. The residuals of correct observations decrease as the number of components increases. When all the components are used, the input data will be reproduced exactly, even though they are independent of those used to construct the components. The situation is analogous to the fitting of a series of N data points with an N-dimensional polynomial. The use of all components will not result in good error detection, however, since the errors will be fitted as well as the correct observations. The residuals of erroneous observations will decrease with an increasing number of components at first, then increase as the higher-order components fit the errors.

A thorough testing of the principal component technique involves a consideration of the following points:

(i) The assignment of variables to stations (S-mode analysis) or days (T-mode analysis).

(ii) The form of input data supplied, e.g. whether to use 'station anomalies', representing departures from the long-period station mean, or 'daily anomalies', representing departures from a mean for the day. There is also the choice of basing the analysis on a correlation or covariance matrix.

(iii) The domain covered, i.e. whether the United Kingdom is considered as a whole or divided into smaller regions.

(iv) Whether it is better to separate the seasons or perform a single 'mixed season' analysis.

(v) The number of years' data that need be used.

It was found that none of these factors affected the performance of the technique by very much. The current quality-control system uses a covariance-based T-mode analysis of daily anomalies for the whole of the United Kingdom using data taken from all seasons in the period 1972–79. Since the residuals based on 1 year of data are only a few per cent larger than those based on 8 years, little is lost by computing components from only 1 year of data. Typical residuals obtained from such annual analyses are presented in Table I.

Table I. *Residuals associated with the principal component technique*

	Minimum temperature r.m.s. residuals (°C) from:			Sunshine r.m.s. residuals (hours) from:		
No. of components	Original data	Independent data	Erroneous observations	Original data	Independent data	Erroneous observations
0	2.19	2.16	2.22	2.52	2.52	2.50
1	1.69	1.71	1.75	2.10	2.11	2.10
2	1.43	1.45	1.46	1.92	1.95	1.96
3	1.33	1.36	1.39	1.76	1.79	1.79
6	1.13	1.20	1.23	1.49	1.54	1.54
9	1.02	1.13	1.18	1.33	1.41	1.40
12	0.94	1.09	1.15	1.23	1.32	1.33
15	0.88	1.05	1.11	1.15	1.25	1.29
18	0.83	1.03	1.10	1.07	1.19	1.28
21	0.79	1.01	1.10	1.02	1.15	1.29
24	0.75	1.00	1.10	0.97	1.11	1.31

Usually the most difficult problem in any application of principal components is to decide how many components to use. For present purposes this number can be defined as that which produces the minimum r.m.s. residual of erroneous observations. The complexity of the patterns being matched depends mainly on the number of stations used and it was found that the best number of components could be expressed as a fraction of the number of stations used. The linear relationship will hold only so long as the best number of components is much less than the number of (independent) days, since, if less than the number of stations, this places an upper limit on the number of components required to account for all the variance.

The more highly correlated the data, the fewer the number of components that need be used. Thus for minimum temperature it was found that the best number of components to use was 6% of the number of stations while for the less correlated sunshine data the figure rose to 9%. As the complete network of 350 sunshine stations will provide more correlated data than that used here (197 stations), it may be speculated that the best number of components will be 8% of the full number of sunshine stations. The best number of components to use may therefore be estimated as

$$600 \times 6\% = 36 \text{ for minimum temperature}$$

and

$$350 \times 8\% = 28 \text{ for sunshine.}$$

The minimum in the relationship between the magnitude of the residual and the number of components is very flat, as can be seen from Table I. The current quality control uses only 15 components, and the residuals of erroneous observations could be decreased by 10% by increasing this number to about 30.

Seasonal variations in the r.m.s. residuals of erroneous observations reflect variations in the input data. For minimum temperature they are slightly larger in winter than in summer, while for sunshine they range from 0.8 hours in winter to 1.7 hours in summer. Geographical variations in the r.m.s. residuals of minimum temperature are illustrated in Fig. 3 and range from 1.5 °C in the data-sparse Scottish Highlands to 0.7 °C in, for example, parts of Northern Ireland and southern England. Residuals of summer sunshine reveal a similar dependence on the station network with r.m.s. values ranging from less than 1.5 hours over much of England to over 2 hours in other districts. In winter, however, geographical variations are much smaller. This is because there are a large number of sunless days for which in data-sparse areas the estimates are easy to make.

6. Estimation by near neighbours

Four main steps were used in the development of a near neighbour scheme:

(i) The eight most highly correlated stations were chosen to act as 'neighbours'.

(ii) The neighbouring observations were 'reduced' to those appropriate to the site characteristics of the test station by using the conventional conversion factors of percentage of monthly average for sunshine and difference in monthly average for temperature. The monthly ratios or differences were not used directly but were meaned over all months.

(iii) A simple scanning procedure was used to eliminate erroneous observations at neighbouring stations which degrade the accuracy of the estimates derived from them.

(iv) The acceptable estimates were combined using a weighting scheme based on an inverse square law in correlation space.

Since the quality of the estimates is unaffected by whether or not there is an error at the test station no distinction need be drawn between correct and erroneous observations — their r.m.s. residuals will be the same. Table II shows that these values lie around 1.0 °C for minimum temperature and 1.1 hours for daily sunshine, very similar to the figures obtained from principal components. The similar standard of estimates obtained for sunshine is due to the competing effects of poorly correlated and non-normally distributed data, the former favouring principal components and the latter near neighbours. The gain of principal components over near neighbours as the data become less well correlated is demonstrated by the more pronounced geographical variations for near neighbours (Fig. 4) than for principal

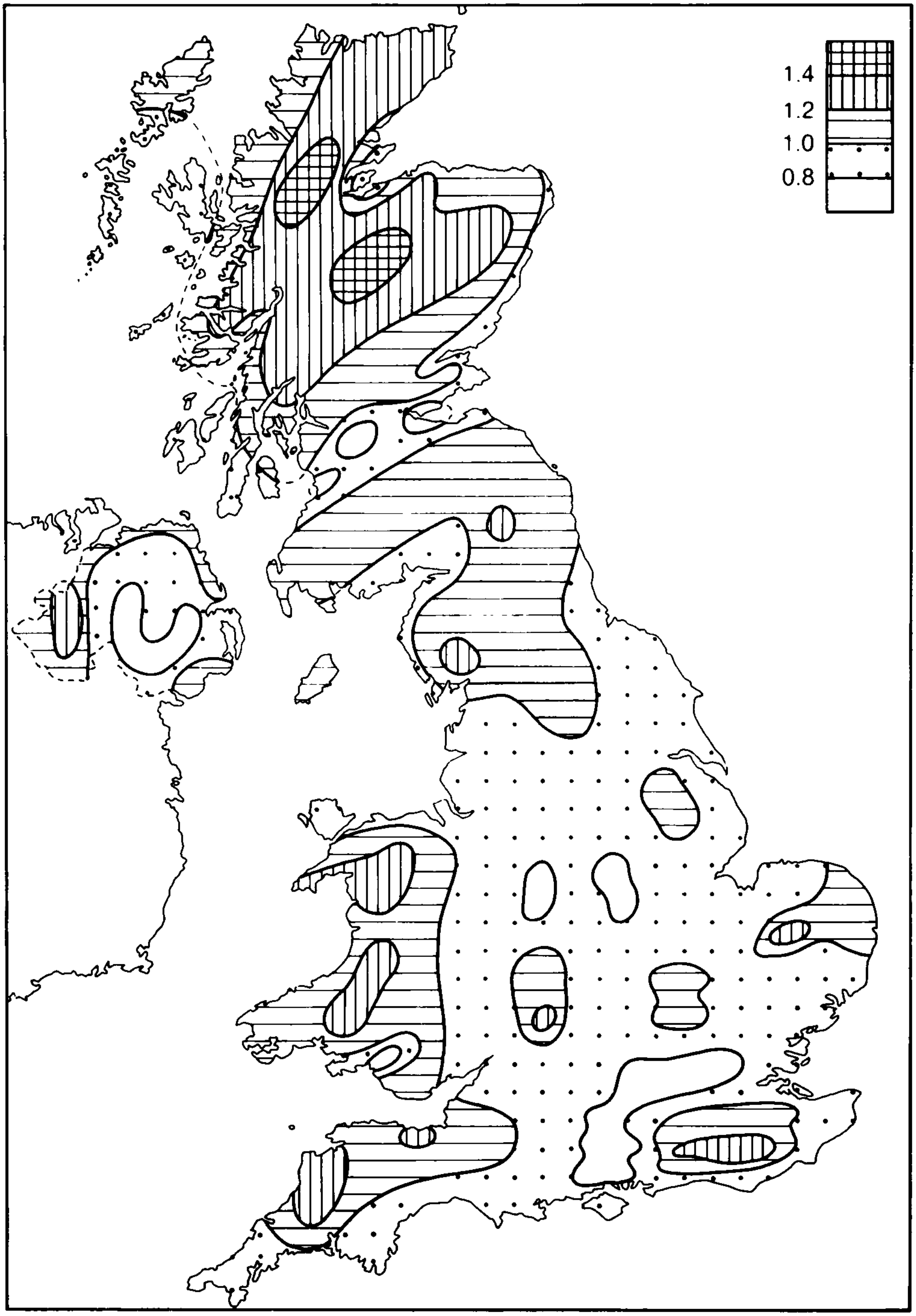


Figure 3. Geographical variations in root-mean-square residuals of minimum temperature (°C) obtained from principal component analysis (15 components, 1973 tested on 1978).

Table II. *Residuals associated with the near neighbour technique*

Regression technique	Data used	r.m.s. residuals Min. temp. (°C)	Sunshine (hours)
Constant difference/Ratio	30-year averages	1.00	1.10
Constant difference/Ratio	1-year calibration period	1.02	1.10
Constant difference/Ratio	4-year calibration period	0.95	1.08
None (station = neighbour)	Current month	1.16	1.11

components (Fig. 3). For the highly correlated dense networks near neighbours holds a small advantage, whereas for the less well correlated data-spare areas principal components is clearly superior.

7. Estimation from the current month

One requirement of an operational quality-control system which has to be recognized is the need to cope with new stations. For these stations past data are unavailable for the calculation of principal components or near neighbour regressions, and substitute information has to be derived from data for the 'current' month, i.e. the month being quality controlled. This has the advantage that the data to be estimated are not independent of those being used to form the components or regressions, and so the estimates of correct observations will be better than those based on past data. The disadvantage is that the erroneous observations either contaminate the components or have to be excluded from the regressions, and so their estimates are worse than those obtained from past data.

For the near neighbour technique the data can be scanned and likely errors removed before the regressions are developed. It was found that the r.m.s. residual of 1.10 hours for sun decreased to 1.00 hours for correct observations but increased to 1.19 hours for erroneous observations. For minimum temperature the constant difference approximation was replaced by a conventional linear regression made suitable by the fact that it was being tested only on dependent data. This led to the r.m.s. residual of 1.00 °C decreasing to 0.71 °C for correct observations but increasing to 1.17 °C for erroneous observations. From these figures it can be deduced that the current month technique is providing a similar standard of quality control to that obtained from past data.

For principal components the current month approach is less satisfactory for two reasons:

(i) The missing components for the new stations have to be estimated from data for the current month. Although the components are biased towards the sample of data on which they were tested, some of the directness of the near neighbour technique in using exactly those data which are to be estimated is lost.

(ii) The technique does not lend itself to the scanning and removal of likely errors before the components are calculated.

Thus it was found that for minimum temperature, r.m.s. residuals based on 15 components fell from 1.05 to 0.93 °C for correct observations but rose from 1.11 to 1.78 °C for erroneous observations.

8. Flagging routines

The overall performance of any quality-control procedure depends on:

(i) the accuracy with which true values can be estimated on occasions of erroneous observations,

(ii) the number of errors which are not queried (type I error), and

(iii) the number of invalid queries raised (type II error).

So far attention has been concentrated on item (i) and the residuals of erroneous observations. The accuracy with which correct observations are estimated is also relevant, however, since this affects the number of invalid queries raised.

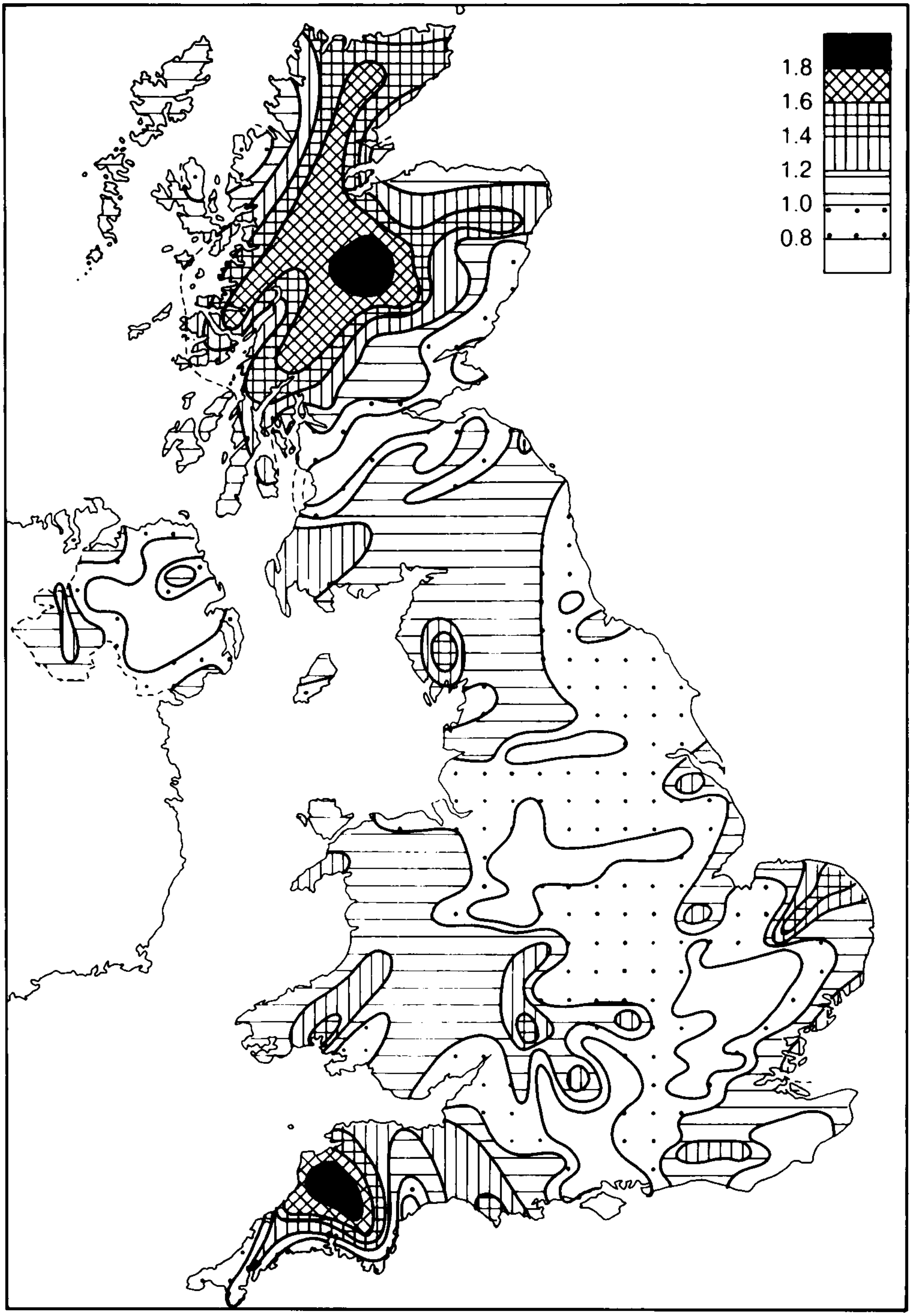


Figure 4. Geographical variations in root-mean-square residuals of minimum temperature (° C) using near neighbour technique (1973 tested on 1978).

A reasonable measure of the effectiveness of a quality-control system is the proportion of error variance detected. No absolute measure of merit is possible, however, since subjective judgement is required to decide whether to aim for quality and minimize the proportion of error variance detected, or to go for economy and minimize the number of invalid queries raised.

The best way of raising queries is to flag observations for which the residual exceeds a specified number (S) of standard deviations of the residuals. It is also advantageous to supply an absolute threshold (D) to prevent small differences from being queried. The current quality control uses only S, but it is set at such a high value (3.25) that small values of D will have little impact.

There are a number of points of interest concerning the calculation of the mean and standard deviation (SD) of the residuals:

(i) All stations in the United Kingdom could be used, but high and low variances of residuals in differing regions could have adverse effects on the efficiency of the flagging in each district. Alternatively, therefore, the mean and SD could be calculated from stations in districts about one-tenth the size of the United Kingdom (say) or in smaller groups of counties.

(ii) The systematic error in the residuals over a region could be removed.

(iii) The residuals could be trimmed before the mean and SD are calculated.

All these options were tested on principal components, for which the current scheme uses residuals analysed by district, untrimmed, but with the systematic error removed. For near neighbours only the conventional procedure of using the residuals from the nominated neighbours was tried, but there is no reason why the other options could not be used. It should be noted that the 'flagging routines' can affect the overall accuracy of a technique. The r.m.s. residuals presented so far were calculated about a mean of zero; if systematic errors over a district can be removed, then this increases the accuracy of the technique.

For minimum temperature, the smallest residuals of erroneous observations have been seen to be associated with 22 components (6% of the 373 stations used). When the performance was assessed in terms of the numbers of type I and type II errors, the continued decrease of the residuals of correct observations with an increasing number of components led to the 'best' number of components being increased to 30. Removing the systematic error in the residuals, however, produced a marked improvement in the results for a small number of components, leading to a stable performance between about 5 and 50 components.

The tuning of the quality control of minimum temperature by variation of D and S is illustrated in Fig. 5 for both near neighbours (past data and current month approaches) and principal components (with the options used by the current operational system). It can be seen that near neighbours, and in particular the current month approach, has slight advantages over principal components. In general, however, about 80% of errors can be detected by raising twice as many queries as there are errors. A point of interest is the extent to which the flagging threshold of $S = 3.25$ used in the current system is geared to economy. The number of invalid queries raised is very small, but this is only achieved at the expense of 40% of the errors remaining undetected.

The tuning of the quality control of sunshine is illustrated in Fig. 6 and reveals three main points of interest:

(i) Errors become more difficult to detect as their frequency decreases below 50%, a phenomenon discussed in the next section. In order to make comparisons with minimum temperature, therefore, the frequency of errors has been increased from 1 in 190 to 1 in 100. Fig. 6 shows that this almost halves the number of invalid queries when expressed as a proportion of the number of errors.

(ii) Analysing residuals by a small group of counties (as in a typical near neighbour scheme) is less effective than analysing them by district. This is attributed to the non-normal distribution of sunshine, which increases the sampling variability of the residuals. This renders the mean and SD calculated from a small number of stations a poor guide to the identification of errors.

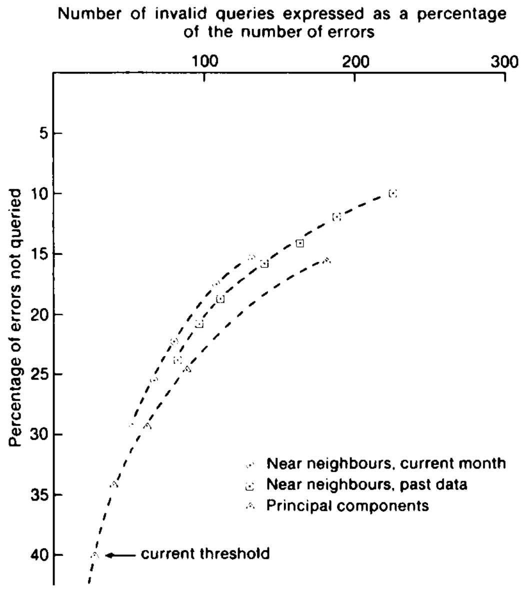


Figure 5. Effect on the number of errors not queried and the number of invalid queries of tuning the quality control of minimum temperature (1973 tested on 1978) by variations of S and D.

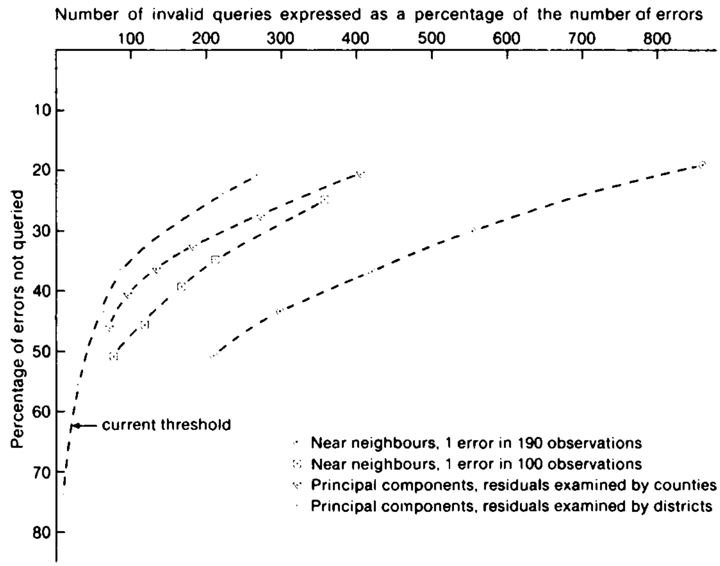


Figure 6. Effect on the number of errors not queried and the number of invalid queries of tuning the quality control of daily sunshine (1979 tested on 1983) by variations of S and D.

(iii) Near neighbours performs worse than principal components even when the residuals from the latter are analysed by counties. This is because although the residuals from both techniques have a similar mean, those for principal components have less scatter, the residuals being smaller for the more isolated stations. It is these isolated stations which generate the most queries and so an improvement in the estimates for these stations helps to reduce the number of invalid queries raised. These arguments apply to temperature as well as sunshine, but the different rates of correlation decay cause the effect to be much greater for sunshine than temperature.

9. Effect of the frequency of errors on their detection

A decrease in the frequency of errors is associated with an improvement in the accuracy with which estimates of erroneous observations can be made, but the improvement is only slight. Of more importance is the fact that as the error frequency decreases the detection of those errors becomes progressively more difficult, and the reasons for this are discussed below.

Consider a situation in which a set of observations contains some errors of ±4 °C and that the accuracy (r.m.s. residual) with which true values can be estimated is 1 °C for both correct and erroneous observations. If as many as 50% of the observations are in error then the distribution of residuals is as illustrated in Fig. 7(a). There is good discrimination between the correct and erroneous observations with very little overlap between the two distributions. Suppose next that the frequency of errors was decreased to 1 in 10, a situation illustrated in Fig. 7(b). The relative increase in the number of correct observations has increased the overlap between the residuals of the correct and erroneous observations. If the frequency of errors is decreased to 1 in 100 (Fig. 7(c)), the overlap between the two sets of residuals is increased still further and encompasses almost 40% of the errors.

It should be borne in mind that a decreasing frequency of errors is associated with a *decrease* in the *total* number of queries raised; it is only when expressed as a fraction of the number of errors that a drastic increase in the number of invalid queries occurs. Nevertheless, Fig. 7 does demonstrate that, all other things being equal, it becomes progressively more difficult to discriminate between correct and erroneous observations as the proportion of errors decreases below 50%.

The situation illustrated in Fig. 7 approximates to that pertaining to the quality control of minimum temperature, although in the latter case the errors are not fixed at 4 °C and so the spread of the residuals of erroneous observations will be greater than that indicated. Nevertheless, it can be seen how the current threshold of $S = 3.25$ is close to the point at which an observation is just as likely to be in error as it is to be correct. If S is decreased below this value the proportion of errors detected increases but the number of invalid queries rises rapidly.

The threshold to be chosen for raising flags depends on a management decision as to whether to aim for economy or quality. For England and Wales, areal quality control occupies one-sixth of the time of four persons involved in all aspects of the quality control of temperature and sunshine, and most of this is involved in the oral or written checking of observations. There is therefore little extra staff effort involved in aiming for quality rather than economy. For temperature it seems reasonable to generate twice as many queries as errors, corresponding to the setting of $D = 2.5$ and $S = 2.0$ (as opposed to

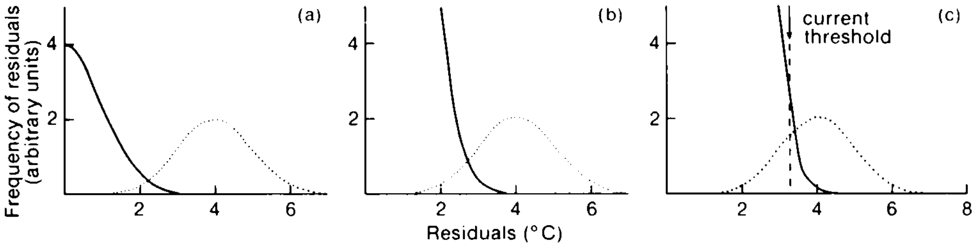


Figure 7. Effect of proportion of errors on their ease of detection, where the proportion of errors is (a) 50%, (b) 10% and (c) 1%. Solid lines indicate residuals of correct observations, dotted lines residuals of erroneous observations.

$S = 3.25$). Most of the extra errors detected will be small, however, mainly between 2.5 and 3.25 °C. So far it has been tacitly assumed that, once a query has been raised, the human scrutineer is able to make the correct decision as to whether an observation is in error or not. With the small errors under discussion the success rate may be small but will depend on the experience of the scrutineer.

10. Conclusions

The principal component and near neighbour techniques provide similar standards of quality control, with r.m.s. errors of estimates of about 1 °C for minimum temperature and 1.2 hours for daily sunshine. Principal components gains over near neighbours as the data become less well correlated and hence has the advantage of performing better at the more isolated stations. The near neighbour technique, however, produces the better estimates for new stations for which past data are unavailable. The effect of non-normally distributed data is to degrade both the estimates obtained from principal components and the effectiveness of flagging routines based on only a small number of stations, as in a typical near neighbour scheme.

The current quality-control system is close to being optimal but the following points are worthy of note:

(i) The residuals of erroneous observations can be reduced by about 10% by doubling the number of components used from 15 to 30. However, the removal of systematic errors on the one hand, and the effect of the residuals of correct observations on the other, combine to produce a standard of quality control which changes little over a wide number of components.

(ii) The system of calculating principal components from every third day over an 8-year period could be replaced by one based on using every day's observations from only 1 year of data. The decrease in accuracy for established stations (about 5%) would be offset by a simpler updatable system in which the number of new stations would be kept to a minimum (3%).

(iii) The current level of tuning of $S = 3.25$ is geared to economy by raising queries at a threshold at which observations are just as likely to be in error as they are to be correct. By generating twice as many queries as errors, the threshold could be reduced to about 2.5 °C, but the potential benefits would probably be lost through the inability of the human scrutineer to correctly identify these small errors.

The overall standard of quality control attained by the use of the conventional station network may be considered as adequate for temperature but unsatisfactory for sunshine. This is a consequence of the reduced network of stations and greater correlation decay for sunshine compared with temperature. The position with regard to sunshine is likely to change dramatically in the future as an increasing emphasis towards radiation is accompanied by the availability of satellite-derived observations. These should make it possible to estimate and quality control sunshine and radiation from a relatively sparse network of ground stations.

References

Bryant, G.W.	1979	Archiving and quality control of climatological data. *Meteorol Mag*, **108**, 309–315.
Hopkins, J.S.	1977	The spatial variability of temperatures and sunshine over uniform terrain. *Meteorol Mag*, **106**, 278–292.
Johnston, R.J.	1980	Multivariate statistical analysis in geography. London, Longman.
Kendall, Sir Maurice	1980	Multivariate analysis. London, High Wycombe, Griffin.
Richman, M.B.	1986	Rotation of principal components. *J Climatol*, **6**, 293–336.
Spackman, E.A. and Singleton, F.	1982	Recent developments in the quality control of climatological data. *Meteorol Mag*, **111**, 301–311.
Tabony, R.C.	1985	A review of the areal quality control of daily climatological data. (Unpublished, copy available in the National Meteorological Library, Bracknell.)

551.515.41:551.576.11

Cumulonimbus clouds: an introductory review

By D.A. Bennetts*, E. McCallum* and J.R. Grant*
(Meteorological Office College, Shinfield Park)

Summary

This article, on cumulonimbus clouds, is one of a series of teaching papers on mesoscale meteorology developed at the Meteorological Office College. It describes the important physical and dynamical aspects of cumulonimbus development, highlighting the roles of convectively available potential energy and wind shear. The aim is to provide simple conceptual models to help in the interpretation of observations; it is not a comprehensive review.

1. Introduction

All atmospheric motion is ultimately caused by solar energy but there are many ways in which this becomes available. One of the more direct is caused by the ground heating up and this in turn warming the air in contact with it. Differential heating, caused for example by variations in the nature of the ground, leads to local increases in the air temperature and in these regions the air can become buoyant and rise as a thermal, the strongest eventually developing into convective or cumulus clouds. Such clouds are often small and herald fine, sunny weather, but sometimes they develop vigorously until they extend over the depth of the atmosphere and produce torrential rain and hail, frequently accompanied by thunder and lightning. This article discusses the structure and evolution of these very large convective clouds which are often colloquially referred to as thunderstorms, although of course the presence of thunder is not essential to their formation and evolution. The aim of the article is to provide simple conceptual models to help in the interpretation of observations; it is not a comprehensive review. For more information about thunderstorms see Atkinson (1981) and Ludlam (1980) both of which provide comprehensive reference sections.

2. Quantitative description of the growth of a thunderstorm

Thunderstorms can be initiated by many atmospheric processes but to illustrate some of the important features of a developing cloud it is helpful to consider the relatively simple mechanism outlined above. As a thermal rises from the ground it cools adiabatically until eventually condensation takes place. At first the cloud droplets are small, typically 1 or 2 μm in diameter, but they grow rapidly, initially by condensation and later through collisions. If the temperature of the thermal decreases sufficiently then a few of the droplets will freeze at about $-15\,^{\circ}$C, and by about $-35\,^{\circ}$C (typically at a height of 7 km) the cloud is almost completely glaciated. The drops of water and ice particles (if present) eventually become sufficiently heavy that they fall through the buoyant updraught, growing even larger by 'sweeping up' smaller droplets, and emerge from the base of the cloud as rain, hail or snow. Below cloud base the air is unsaturated and often at a temperature above $0\,^{\circ}$C; in consequence any hail and snow begin to melt and the raindrops partially evaporate, both processes leading to a cooling and moistening of the air as the latent heats of melting and evaporation are extracted. The cold air sinks and forms a downdraught which spreads out on encountering the ground to produce a gust front at its boundary with the ambient air and creates the localized, strong, cold winds, squall lines and large wind direction changes that are frequently associated with thunderstorms.

---

* Now at Meteorological Office, Bracknell.

Thunder and lightning, although spectacular, are in fact of minor importance to the storm evolution, and severe storms can occur without their presence. The severity of a storm is essentially determined by the strength and duration of its updraught and downdraught for which the model described above gives a qualitative explanation. However, invariably we wish to quantify the effects, for unless the amount of rain and the strength of the winds can be related to the initial environmental conditions, it will not be possible to give advance warning of the characteristics of such storms.

3. Parcel theory

The simplest model of convection is called parcel theory which is based on the assumption that a positively buoyant parcel of air moves upwards without disturbing the environment. This is demonstrated on the tephigram shown in Fig. 1. Consider a parcel of air within a thermal rising from the ground. Initially it is unsaturated and as it rises it cools adiabatically, i.e. the parcel conserves both its potential temperature and humidity mixing ratio. In Fig. 1 this behaviour occurs in the region below point A. When the parcel reaches point A the air becomes saturated, cloud forms and further ascent follows the saturated adiabat, i.e. the parcel conserves wet-bulb potential temperature (θ_w). This behaviour occurs between points A and B, and throughout this part of the ascent the latent heat release is sufficient to keep the parcel buoyant, and therefore it accelerates until it reaches point B where it attains its maximum vertical velocity. All the thermodynamic energy released between A and B (shaded area — on a tephigram such areas are proportional to the energy available for convective processes) is translated into kinetic energy. Above B the parcel is colder than its environment and the energy transfer is reversed, kinetic energy is converted to thermodynamic energy, the process continuing until the hatched area above B is equal to the shaded area below B.

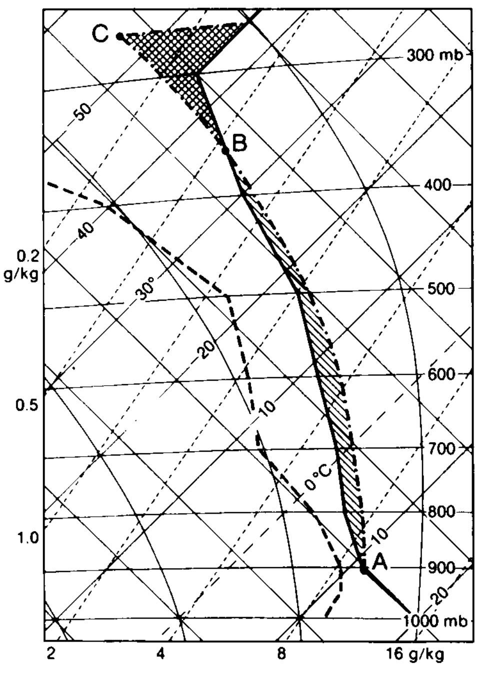


Figure 1. Tephigram illustrating the parcel theory. For details see text.

However, as the cloud develops, the assumption that it moves without disturbing the environment no longer holds. Observations readily show that at the cloud boundary the cloudy air mixes with the dry environmental air. Dryer air, with a much lower θ_w than the cloudy air, is 'entrained' into the cloud and the development is slowed down, so that in practice the cloud top rarely overshoots point B. Unfortunately it is impossible to quantify mixing in this simple model as this depends crucially on the ambient winds — a feature not included. It is therefore necessary to develop more sophisticated models of convection.

Two parameters govern the severity of convective storms; the convectively available potential energy (CAPE) and the vertical structure of the wind. The CAPE is the available potential energy that can be released through convection and is represented by the shaded area between A and B in Fig. 1. Broadly speaking, the larger the CAPE the more active the storm. However, the CAPE expresses only that energy that can be released by a parcel during ascent; it does not impart any organization to the release. In any given volume of atmosphere the CAPE can be released through many small clouds, or through one severe storm. The choice between these two extremes is governed by the ambient wind.

4. Single-cell clouds

When there is no wind a buoyant parcel of air rises vertically. As it rises, cloud droplets and then rain, hail and/or snow form. Eventually the precipitation particles achieve sufficient size for their fall speeds to exceed the updraught speed and they fall towards the ground. Initially their descent is within cloudy air and the particles continue to grow through accretion of cloud water. As they fall, they exert a slight drag on the air which gradually reduces the speed of the updraught. In addition any hail may melt, thereby cooling the air, further reducing the updraught. Eventually the precipitation falls clear of cloud and starts to evaporate. All these processes assist in the production of a downdraught which, because there is in this case no wind, is situated directly beneath the updraught. This downdraught therefore cuts the inflow to the cloud and the cloud rapidly decays. The active lifetime of these clouds is typically ½ hour; but some cloud at high level may persist for much longer.

Conditions of no wind are rare within the atmosphere. However, the wind is often uni-directional, as for example in the cold air well behind a cold or occluded front; Fig. 2 shows an example of a model of a cloud growing in uni-directional wind shear. Fig. 2(a) shows an early stage of cloud development, before rain has formed, and the updraught, leaning slightly to the right as a consequence of the ambient shear, is clearly visible. A much later stage of development is depicted in Fig. 2(b). Of particular note is the fact that updraught and downdraught coexist. The presence of vertical shear has permitted the precipitation to fall clear of the updraught and the cloud lasts longer than when there was no wind, a typical lifetime now being ¾–1 hour. Below 700 mb the downdraught is the dominant feature. When it reaches the ground it spreads out as a gust front, undercutting the warmer, environmental air and ultimately cutting off the low-level inflow to the cloud. The gust front is discussed in more detail later.

(a) *Steering level*

In Fig. 2, for illustrative purposes, the wind speed at the ground was chosen to be zero, and the wind increased with height. In consequence the cloud tended to move towards the right at some speed greater than zero, but slower than the winds at high level. The level at which the wind speed equals the cloud speed is referred to as the 'steering level' and in this example is at about 700 mb. As a general rule the height of the steering level can be determined from the height of the cloud base (h_{base}) and the height of the cloud top (h_{top}), and will lie at approximately

$$h_{base} + \frac{1}{3}(h_{top} - h_{base})$$

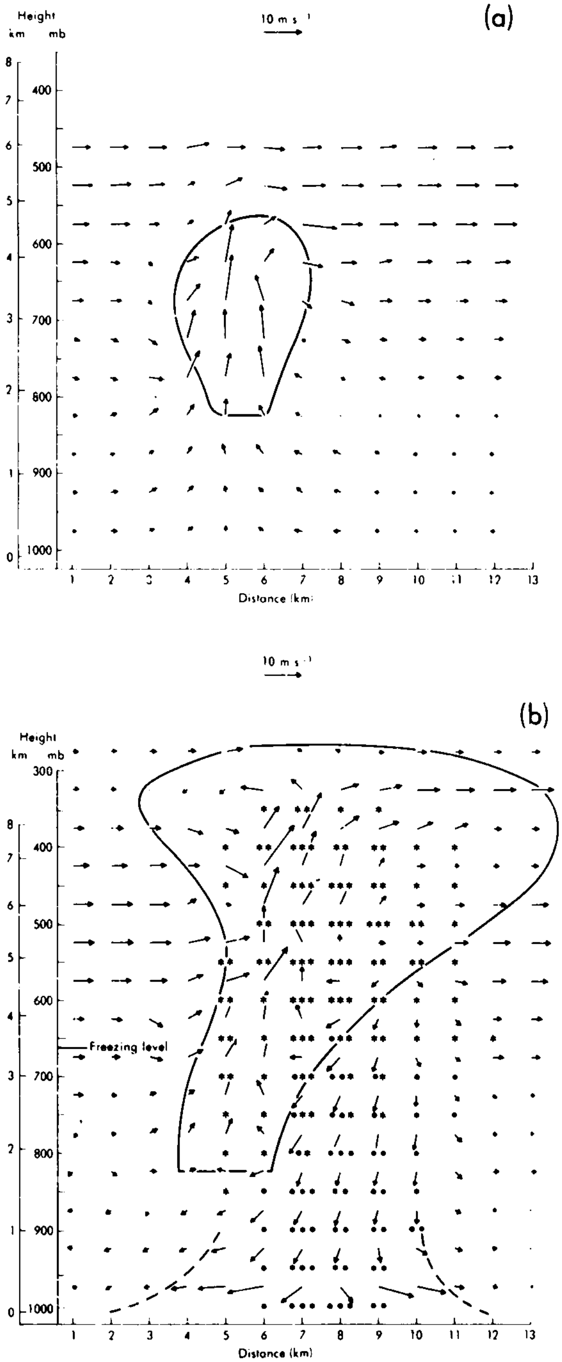


Figure 2. Model of isolated cumulonimbus cloud growing in uni-directional wind shear depicting (a) an early stage of development and (b) a more mature stage. * and • indicate snow and rain, intensity proportional to the number of symbols (from Bennetts 1983).

for all single-cell cumulonimbus clouds, and the clouds will slope 'down shear' as shown in Fig. 2 (note that the steering level changes as the cloud grows). It is useful to look at the structure of the wind relative to this steering level, as in Fig. 3. Using the cloud structure shown in Fig. 2, the low-level inflow comes in from the right (wind speed at 700 mb greater than wind speed at 900 mb) and the upper-level outflow moves away in the opposite direction (wind speed at 500 mb greater than wind speed at 700 mb). Since the cloud also leans towards the right the downdraught cuts the inflow. So, although a cloud growing in uni-directional shear has a longer lifetime than one growing in no shear, it still remains essentially a short-lived storm. To achieve a long-lived storm it is generally necessary to have 'directional shear' so that the downdraught falls to one side of the inflow. This aspect will be discussed in detail in the section on multicelled storms.

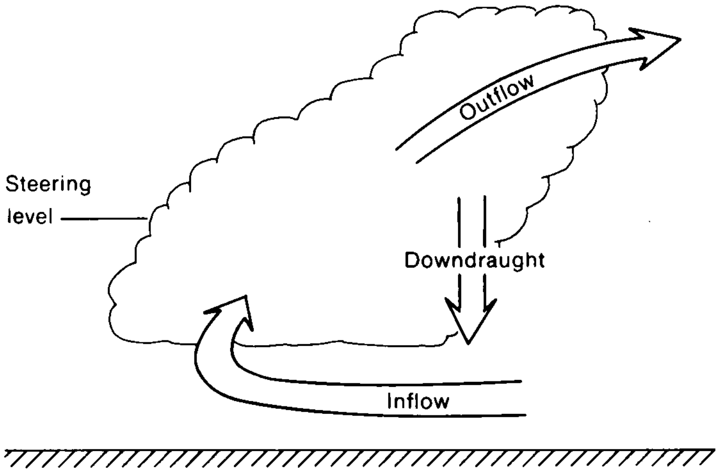


Figure 3. Schematic diagram of internal motion relative to the cloud.

(b) *The gust front*

The gust front is typically 500–1000 m deep and spreads out at 5–10 m s^{-1} relative to the cloud, but, because the depth and speed are so dependent on both the strength of the storm and the structure of the low-level winds, observed values vary widely. The boundary between the cold density current and warm environmental air is characterized by large changes in both wind speed and direction. The boundary-layer air is forced over the nose of the cold air, inducing ascent and creating a narrow region of marked convergence. Both the convergence and induced ascent are strongest where the outflowing cold air opposes the (undisturbed) low-level wind.

5. Multicelled storms

In the previous section it was noted that in conditions of no wind, cells were short-lived because the downdraught developed directly beneath the updraught cutting off the supply of moist low-level air. Uni-directional shear lengthened the lifetime of the cloud by permitting updraught and downdraught to coexist for a short time, but, even in these conditions, the inflow was eventually disrupted by the downdraught.

However, if the downdraught is displaced to one side of the inflow, much longer-lived clouds can develop. This can occur if the wind changes direction with height; for example, consider the hodograph shown in Fig. 4(a). There is no longer a level at which the cell motion matches both the wind speed and direction. However, the cell speed remains similar to the 700 mb wind and always lies within the

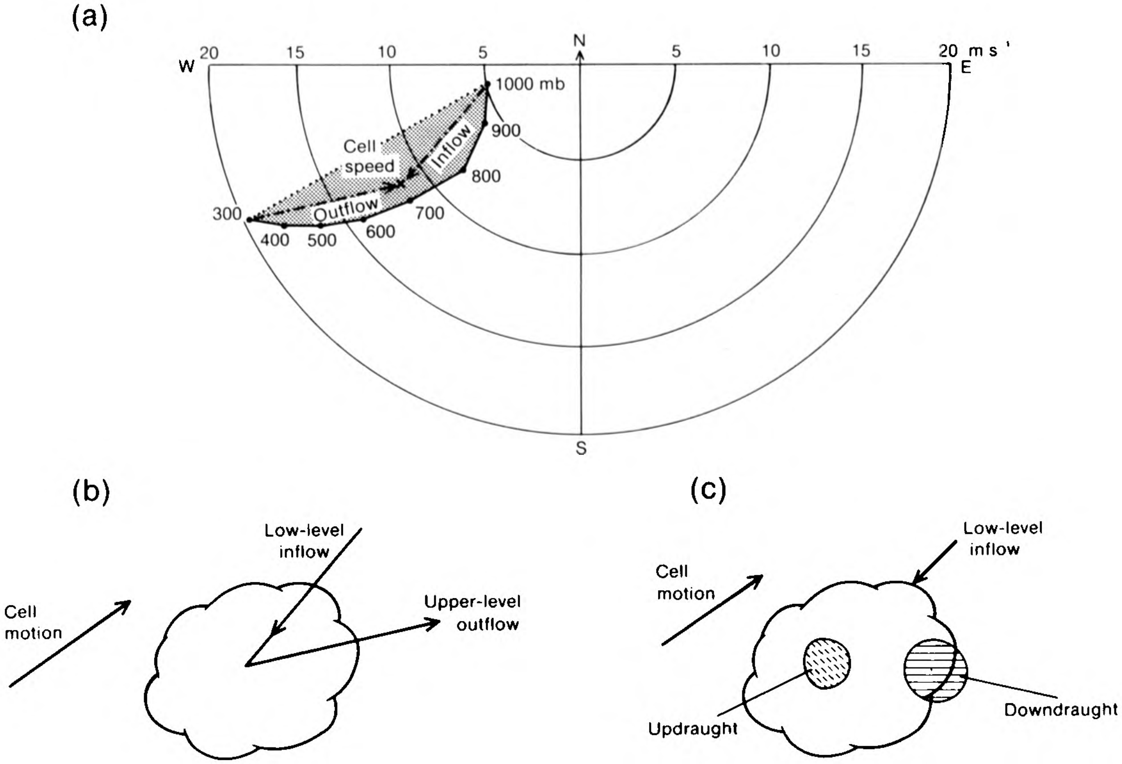


Figure 4. (a) Hodograph showing change in wind with height. The stippled area indicates the 'envelope' of the hodograph. (b) Directions of cloud-relative inflow and outflow. (c) Positions of updraught and downdraught.

'envelope' of the hodograph. Relative to the cell the low-level wind enters the cloud from the north-east and leaves towards the east-north-east (Fig. 4(b)). In consequence the downdraught is situated on the eastern flank, clear of the inflowing air, as shown in Fig. 4(c). Obviously as the downdraught spreads out it will eventually cut the inflow, but the more the downdraught is separated from the inflow the longer the elapsed time before it is cut, and hence the longer the life of the cell.

Typical lifetimes of cells growing in different conditions are as follows:

Vertical shear	Lifetime of cloud
No wind	½ h
Uni-directional shear	¾–1 h
Directional shear	1 h

6. Daughter cells

Since the downdraught forms after the formation of precipitation, i.e. late in the evolution of a cell, any increase in cell lifetime produces a disproportionate increase in the lifetime of the downdraught. In consequence the downdraught, and hence the strength and duration of the gust front, is much increased in clouds growing in directional shear. In such cases the convergence at the gust front may be strong enough to lift boundary-layer air above its condensation level. This is evident in the frequent observations of small cumulus round the base of mature cumulonimbus clouds. If the gust front is moving fast the clouds are generally small and rapidly decay. However, if the gust front becomes quasi-stationary (i.e. slow moving relative to the 'parent' cell) a large quantity of moist boundary-layer air is lifted at one point, sometimes in sufficient quantity to trigger a new cumulonimbus cloud. Such conditions are most likely to occur where the outflow opposes the low-level inflow.

The new cloud is called a daughter cell and may, in time, generate another daughter cell. The collection of individual cells is referred to as the storm. Because the cells always form to one flank of the storm, the storm will appear to move to the left or right of the cells. Since the cells move with the speed of the wind at the steering level, the storm will appear to propagate relative to the winds at all levels.

An example of such behaviour occurred on 5 June 1983 (Hill 1984). During the afternoon a series of six multicellular hail storms moved along the south coast of England Fig. 5(a). The detailed structure of one of the storms (E) is shown in Fig. 5(b). It can be seen that although the storm as a whole, shown by contours of rainfall intensity every 30 minutes, moved along the south coast, individual cells, marked with a cross at 15-minute intervals, had a more northerly track, appearing to form on the south-eastern, and decay on the north-western flank. Detailed calculations show that:

$$\text{Cell speed} = 12.0 \text{ m s}^{-1} \text{ from } 230°$$
$$\text{Storm speed} = 12.5 \text{ m s}^{-1} \text{ from } 260°.$$

Fig. 5(c) shows a hodograph of the midday ascent from Crawley. Low-level winds were from the north-east and high-level winds were generally from the west. Cell speed is marked with a cross, close to the 700 mb wind as expected, and the cell-relative inflow and outflow is illustrated in Fig. 5(d). The downdraught formed on the eastern flank and a daughter cell was generated where the gust front opposed the low-level inflow, i.e. to the east of the parent cell. The evolution of the storm is shown diagramatically in Fig. 5(e).

There is one area of slight disagreement in that the conceptual model predicts new cells forming on the east flank whereas observations showed that they formed to the south-east. This, however, is only an

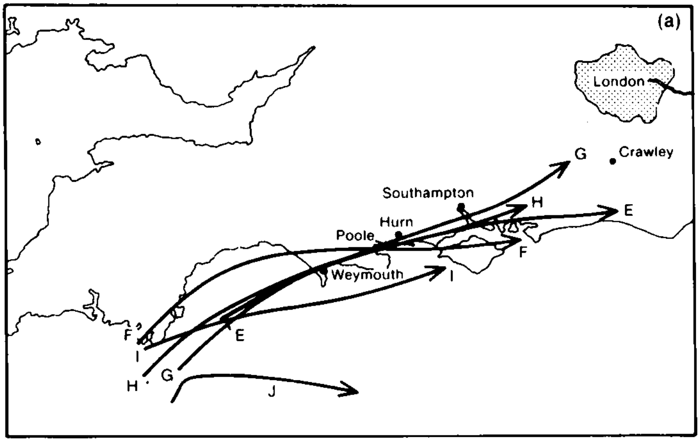


Figure 5. Various aspects of the storms of 5 June 1983. (a) The tracks of the six storms labelled E–J (from Hill 1984). (b) Detailed structure of storm E showing contours of radar reflectivity at half-hourly intervals for the storm, with cell positions (x) marked every 15 minutes. Rainfall rates (mm h^{-1}) as shown in key. (c) Hodograph for Crawley at 1200 GMT. (d) Schematic diagram showing the structure of the parent cell and position of formation of the daughter cell. (e) Schematic plan of storm development showing cell and storm motion.

apparent disagreement for the model predicts the position of formation, whereas the new cells are not seen by radar until some 20–30 minutes later, when the cells have begun to produce precipitation.

Another interesting example of how cell and storm motion can differ occurred on 14 August 1975, the day of the 'Hampstead storm' (Miller 1978). The hodograph for this storm is shown in Fig. 6(a). There was a very marked directional change in the low-level winds, but above 800 mb the wind was almost

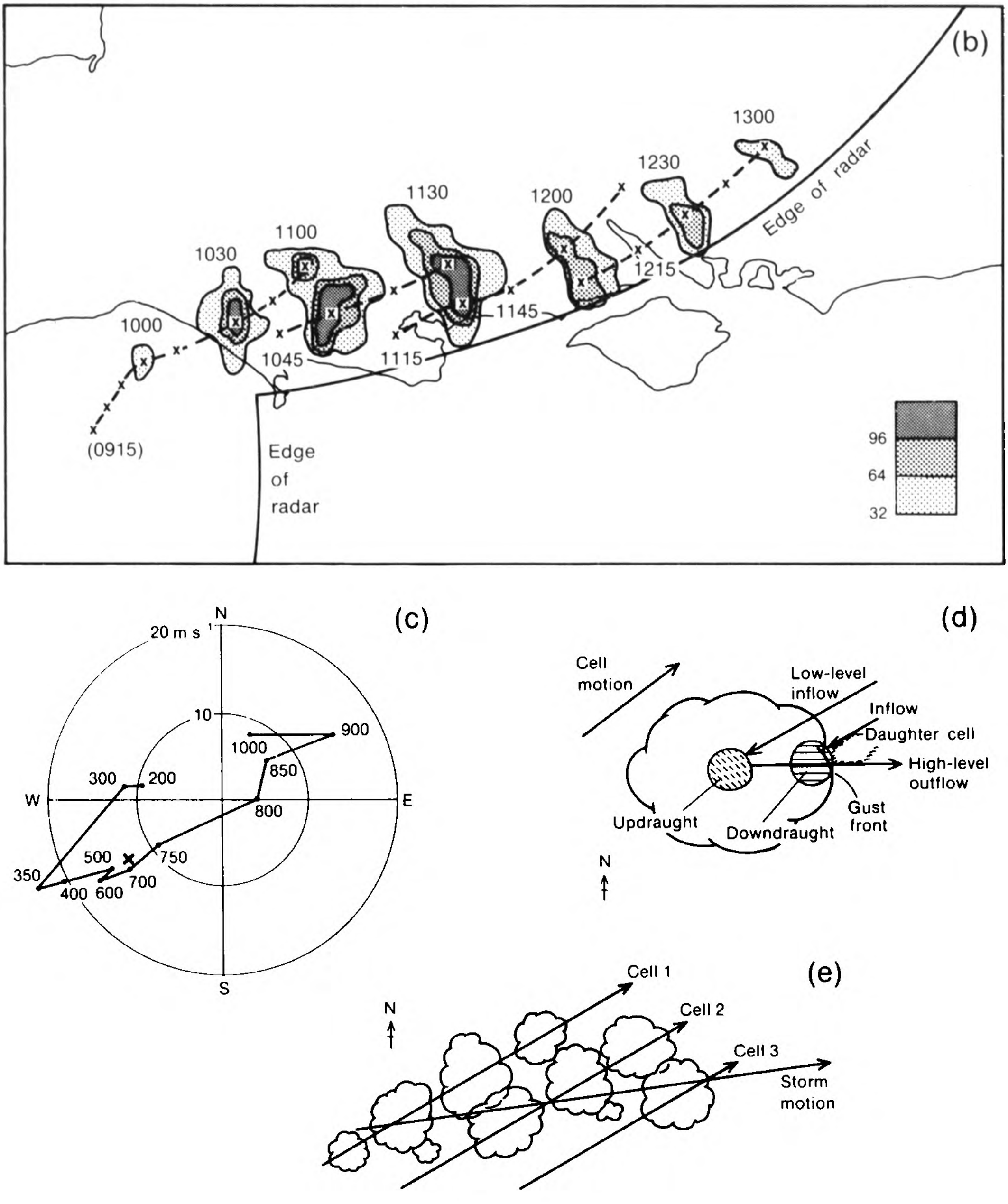


Figure 5 continued.

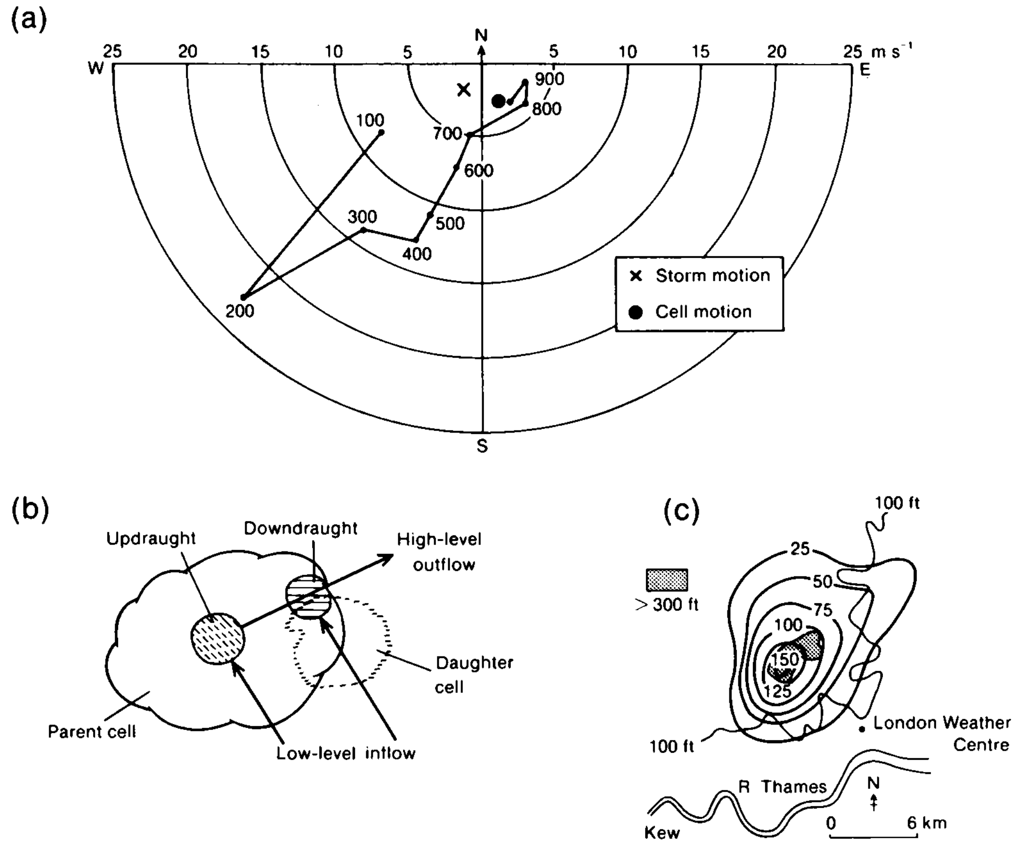


Figure 6. Various aspects of the Hampstead storm, 14 August 1975. (a) Hodograph (from Miller 1978). (b) Cell-relative positions. (c) Isopleths of rainfall (mm) for the period 0900 GMT on 14 August to 0900 GMT on 15 August over north London (from Miller 1978).

uni-directional and increased in strength with height. The mean motion of the cells was towards the north-west. As shown in Fig. 6(b) the downdraught formed on the eastern flank and a daughter cell developed on the south-east flank. Relative to the cell the storm propagated south-eastwards; relative to an observer on the ground the storm appeared stationary (Fig. 6(a)). To the residents of Hampstead cells were seen to form to the south-east, deposit their rain overhead and decay as they moved towards the north-west. This pattern was repeated five or six times and the accumulated rainfall is shown in Fig. 6(c). Fortunately such stationary storms are rare.

A useful rule describing the movement of storms is as follows:

Wind veers with height — storm moves to right (of cell).
Wind backs with height — storm moves to left (of cell).

7. Supercells

One further type of storm remains — the supercell. It is rare in the United Kingdom but common in continental regions where it is responsible for considerable damage mainly through the production of giant hailstones, sometimes up to the size of golf balls. It is much larger than normal storms, often up to

50 km in diameter, and is associated with very strong wind shears over significant depths of the atmosphere. These storms tend to occur when the CAPE is large; typically five to ten times larger than the values generally found in the United Kingdom, e.g. parcel to environment excess temperatures of around 10 °C.

The main characteristic of a supercell is that it is in quasi-steady state with updraught and downdraught coexisting for typically 1–3 hours, but on occasion for up to 12 hours. In some ways a supercell may be seen as the ultimate multicelled storm where the downdraught is so positioned that the daughter cell is co-located with the updraught of the parent cell.

An example of a hodograph associated with a supercell is shown in Fig. 7(a). Consider first the structure of a multicell storm growing in this environment (Fig. 7(b)). Each cell would have a steering level (see section 3(a)) close to that of the mid-level winds, the downdraught would form on the eastern flank, spread out, ultimately cut the inflow and possibly generate a new cell to the east.

However, supercells are always observed to have a motion outside the envelope of the hodograph (see Fig. 7(a)) — precisely why is not yet fully understood. In consequence storm-relative winds are rather different, Fig. 7(c). In particular, mid-level winds are stronger and tend to have an influence on the position of the downdraught which, in supercells, forms on the opposite side of the updraught to the inflow. Maximum convergence occurs directly underneath the original updraught.

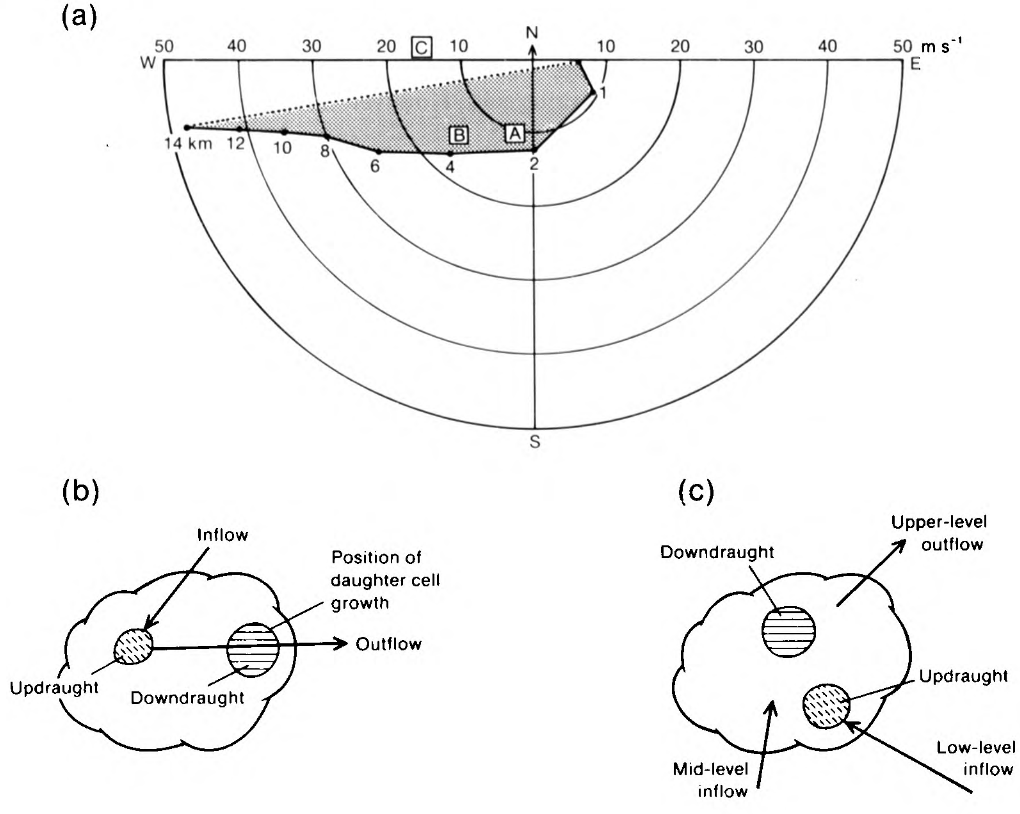


Figure 7. (a) Hodograph associated with a supercell showing individual cell speed at A, multicell storm speed at B and supercell storm speed at C. (b) Schematic diagram of growing multicell storm. (c) Schematic diagram of supercell.

8. Merging storms

Another way in which large cumulonimbus storms can develop is through merging although, to be precise, merging should be viewed as just one aspect of cloud–cloud interactions. Merging can occur in many ways. For example, within a region of forced ascent in a trough line, clouds are frequently forced together and merge. Although each individual event may not be predictable, in general, within the trough line, enhanced convection is expected. However, this is not the only way in which clouds can merge. Consider a uniform, unstable air mass having uni-directional vertical wind shear, such as occurs, for example, well behind a cold front over the sea. Further, assume that within this air mass there develops a population of single-celled clouds. At any given time clouds will exist at all stages of development (i.e. there will be a range of cloud-top heights, the younger the cloud the lower the cloud top). Since the steering level varies during the evolution of the storm the propagation speed of different clouds will vary. Therefore occasionally, by chance, some clouds will move close together and interact. Generally this interaction will reduce the size and strength of both clouds as, due to their close proximity, their inflow regions will overlap and they will compete for the unstable boundary-layer air. However, sometimes the interaction is beneficial and 'merging' results. One way in which this can occur is when the upstream cloud is larger than the downstream (i.e. possibly slightly older). The development in such cases is shown in Fig. 8, and a comparison of the rainfall rate of a single-cell and merger cloud growing in the same environment is shown in Fig. 9. Merging can enhance the rainfall significantly and lower the cloud base.

In consequence, even when the air mass is uniform and conditions are unsuitable for multicellular development, a few large cells can still develop. The occurrence of these is random, depending on the relative position and development of neighbouring cells. However, it is essential to remember that they can, and do, occur.

9. Precipitation

So far, the storms have been discussed in terms of their dynamics. However, it is equally important to know how much precipitation falls to the ground. We have already seen that, in terms of understanding the cloud, the most useful frames of reference are axes moving with either cell or storm velocity. In consequence, for rainfall studies, it is useful to consider the two aspects:

(a) rainfall from a given storm, and
(b) rainfall at the ground,

allowing storms to be studied independent of their translation speed. Before the advent of radar this was difficult, but today storms may be readily studied in their natural frame of reference. It is interesting to reconsider the stationary Hampstead storm for which the mean rainfall total was 100 mm. If that storm had instead had a storm velocity of say 5 m s^{-1}, the rainfall at Hampstead would have been reduced by a factor of about 4, to ~ 25 mm, and the Hampstead storm would have caused little comment, being an average summer thunderstorm.

Indeed, many other severe storms go unnoticed simply because they move quickly and give little rain at any given ground station. It is therefore important to predict those few occasions when the storm velocity is close to zero.

In tackling this problem it is useful to introduce the concept of the 'efficiency' over the lifetime of a storm which may be defined as

$$\text{efficiency} = \frac{\text{total rainfall at ground (cell-relative)}}{\text{total cloud water condensed}} .$$

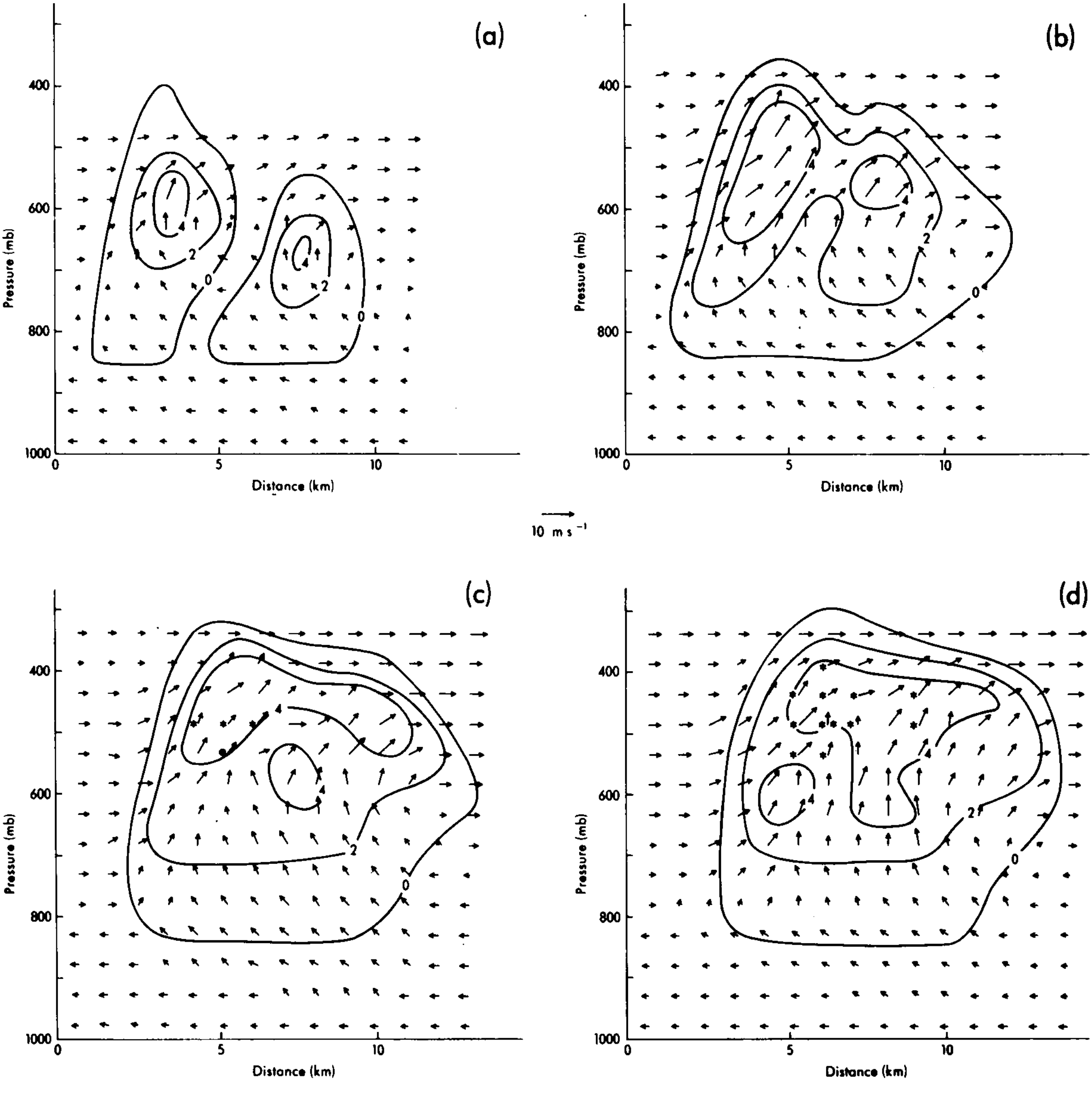


Figure 8. Distribution of cloud water and ice (g kg^{-1}) and wind vectors within clouds at simulated times of (a) 12 minutes, (b) 16 minutes, (c) 20 minutes and (d) 24 minutes. * and • indicate snow and rain (from Bennetts *et al.* 1982).

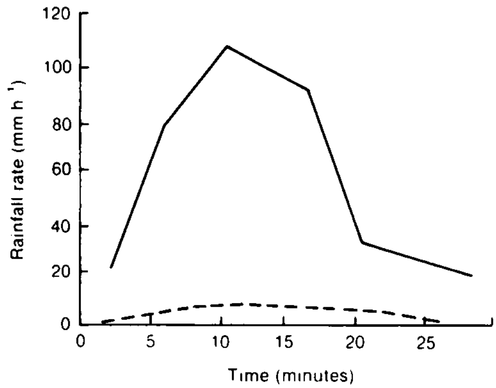


Figure 9. Observed rainfall rates from merged (solid line) and single-cell (dashed line) clouds. On a given day, when the wind direction changed little with height, a population of maritime single-cell clouds was observed by radar. The dashed line shows the maximum instantaneous rainfall rate anywhere within the cloud, plotted as a function of time from initial observation, for a typical cloud. The solid line is representative of the largest (in rainfall rate) cloud observed. (From Bennetts *et al.* 1982.)

This equation may be rewritten as

$$\text{efficiency} = \frac{\text{production of rain}}{\text{CW}} + \frac{\text{accretion}}{\text{CW}} - \frac{\text{evaporation}}{\text{CW}}$$

where CW = cloud water condensed, and the relative magnitude of these terms depends on the trajectory of rain as it falls to the ground. This is illustrated in Fig. 10.

Fig. 10(a) shows the evolution of rain within a single cell growing in no shear. Precipitation is generated fairly high in the cloud, falls through cloud accreting cloud water and growing rapidly until it reaches cloud base, and then evaporates between cloud base and the ground. Compare this to the evolution within a single cell growing in uni-directional shear, Fig. 10(b) (paths are relative to the cloud). In the shear case the ratio

$$\frac{\text{accretive path length}}{\text{evaporative path length}}$$

is very much reduced and therefore the higher the shear the lower the amount of precipitation reaching the ground, in spite of the fact that the lifetime of the cell slightly increases as the shear increases.

Each cell of a multicellular storm has a similar behaviour but because there are several cells the total rainfall can be quite large.

In both single cells and multicells efficiency remains low (~ 30%) as each cell has a large remnant cloud which slowly dissipates after the rain has ceased. In contrast, supercells achieve a steady state. At the end of their life, there is only the remnant from one cell and in consequence they have a much higher efficiency, sometimes up to 80%.

Merging clouds produce high rainfall for a different reason. Here, the presence of the smaller cloud alters the path length ratio, see Fig. 10(c), with precipitation from the upstream cloud falling through the smaller cloud.

10. Conclusions

Parcel theory tells us whether or not convection can occur; the vertical structure of the wind tells us how that convection will be organized. It is therefore important to consider both aspects when forecasting the behaviour of convection.

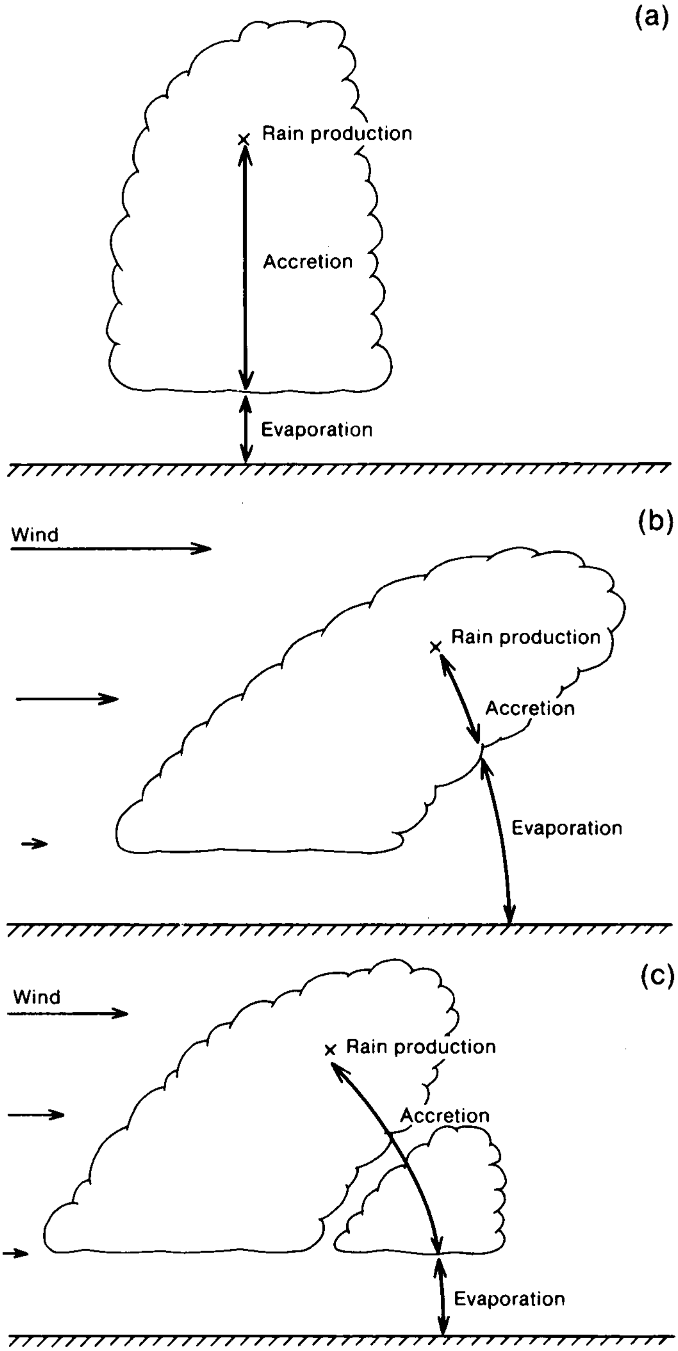


Figure 10. Comparison of accretive and evaporative path lengths for (a) single-cell cloud growing in no shear, (b) single-cell cloud growing in uni-directional shear and (c) merger growing in uni-directional shear.

Although it is difficult to forecast the precise behaviour of cumulonimbus clouds on any given day, the following general rules give some guidance by providing simple conceptual models to assist with the interpretation of such observations as may be available, e.g. radar network data.

After an examination of the tephigram, the vertical wind profile should be studied and classified according as to whether the wind direction is fairly constant throughout cloud depth, or varies markedly with height. The typical behaviour of these two categories follows:

Uni-directional shear

When the wind direction is fairly constant at all levels up to cloud top, convective clouds are generally single celled, short-lived (about ½–¾ hour) and tend to form and disperse under the influence of local effects. Rainfall may be quite heavy, but will rarely last long as the precipitation-induced downdraught tends to cut the cloud's supply of low-level boundary-layer air, leading to rapid decay.

Directional shear

It is not until there is a directional change in the vertical wind profile that long-lived storms become possible. A directional change, with height, permits the downdraught to form to one side of the inflowing air allowing updraughts and downdraughts to coexist for a significant time. This may lead to the formation of daughter cells on one flank of the parent cell and, over a period of 15–30 minutes, the centre of activity transfers from the decaying parent cell to the rapidly growing daughter cell. Such a process can continue for a succession of cells, each cell propagating with the steering level wind, but with the storm appearing to propagate relative to the winds at all levels. In such cases a useful rule is: wind veers with height — storm moves to the right; wind backs with height — storm moves to the left.

The final type of cloud is the supercell. These are very rare in the United Kingdom, but precursors to their formation are large values of the CAPE, typically ten times larger than the values commonly found in the United Kingdom, and very large wind shears.

It is also important to remember that clouds may, on occasions, merge. This is to be expected within, for example, trough lines, but can also occur in relatively uniform air masses. In the latter case the process is random and can occur whenever there is a vertical wind shear such that clouds at different stages of development have different steering levels, and hence slightly different translation velocities. This induces relative motion and they may, on occasions, merge, producing a significant increase in rainfall.

Acknowledgements

We would like to thank all the staff and students at the College who have helped in the development of this paper, especially Miss W.L. Adams who analysed the radar data and produced Fig. 5(b).

References

Atkinson, B.W. 1981 Meso-scale atmospheric circulations. London, Academic Press.

Bennetts, D.A. 1983 Thunderstorms. *In* Howson, A.G. and McLone, R.R.(eds); London, Heineman.

Bennetts, D.A., Bader, M.J. and Marles, R.H. 1982 Convective cloud merging and its effect on rainfall. *Nature*, **300**, 42–45.

Hill, F.F 1984 The development of hailstorms along the south coast of England on 5 June 1983. *Meteorol Mag*, **113**, 345–363.

Ludlam, F.H. 1980 Clouds and storms. Pennsylvania, State University Press.

Miller, M.J. 1978 The Hampstead storm: A numerical simulation of a quasi-stationary cumulonimbus system. *QJR Meteorol Soc*, **104**, 413–428.

551.50:35(829)

The Mobile Meteorological Unit in the South Atlantic 1982–86

By H.E. Brenchley
(Meteorological Office, Bracknell)

Summary

On 2 April 1982 Argentina invaded the Falkland Islands and South Georgia. Within six days the first deployment of the Mobile Meteorological Unit (MMU) had taken place to Ascension Island and on 5 July 1982 the first MMU officer arrived in the Falkland Islands, where the Unit was destined to remain for nearly four years. This article gives an account of the MMU in the South Atlantic from April 1982 to April 1986.

1. Introduction

The Mobile Meteorological Unit (MMU) was formed in the early 1960s as part of the Royal Air Force Tactical Communications Wing. With a ceiling of 20 officer volunteers drawn from Headquarters Branches and outstations of the Meteorological Office and holding active Class CC (Civil Component) Commissions in the Royal Air Force Reserve of Officers, the role of the Unit was to be able to deploy at very short notice, in an emergency, within the NATO area. The Unit was, accordingly, equipped with its own air-portable accommodation, meteorological instrumentation and communication equipment and officers were provided with suitable clothing for operations in warm or cold climates. The Unit's role was exercised from time to time but, by the late 1970s, with the increasing use of host nation meteorological support, the future of the MMU had become uncertain and the morale of its members was not high. The events of April 1982 changed that.

2. Ascension Island

Three days after the invasion of the Falkland Islands (see Fig. 1) found the MMU on standby with four members of the Unit ready to move at 24 hours' notice. The following day, 6 April, instructions were received to deploy to Ascension Island. A (fortuitous) delay enabled the Unit to gather together further charts and equipment suitable for operations in the South Atlantic and departing from RAF Lyneham on 8 April the Unit detachment, comprising two forecasters and two communicator/observers under Squadron Leader W.R. McQueen, arrived with its equipment in the small hours of 9 April at Wideawake airfield, Ascension Island.

On the instructions of the Senior British Officer (SBO), Ascension Island, the MMU was deployed to English Bay at the extreme north of the island, some seven miles from Wideawake airfield. Interference to meteorological radio communications from a nearby transmitter complex, however, combined with the remoteness of the Unit from its aircrew customers quickly confirmed the unsuitability of locating the Unit at English Bay. Further consultations with the SBO resulted in the establishment of the MMU at Wideawake airfield where the equipment was reassembled. The Unit became fully operational on 12 April and provided meteorological support for all air operations out of Ascension Island over the North and South Atlantic. The MMU's contribution to Operation Corporate, the code name for the recovery of the Falklands and South Georgia, had begun.

The MMU 'office' at Wideawake airfield was under canvas (Fig. 2), and domestic accommodation remained hutted at English Bay. Neither were air-conditioned. The shifts worked were long — 24 hours on, 24 hours off — the work-load heavy, and enthusiasm for composition rations quickly waned. The seven-mile transfer before and after each 24-hour shift was described as 'being over roads which required

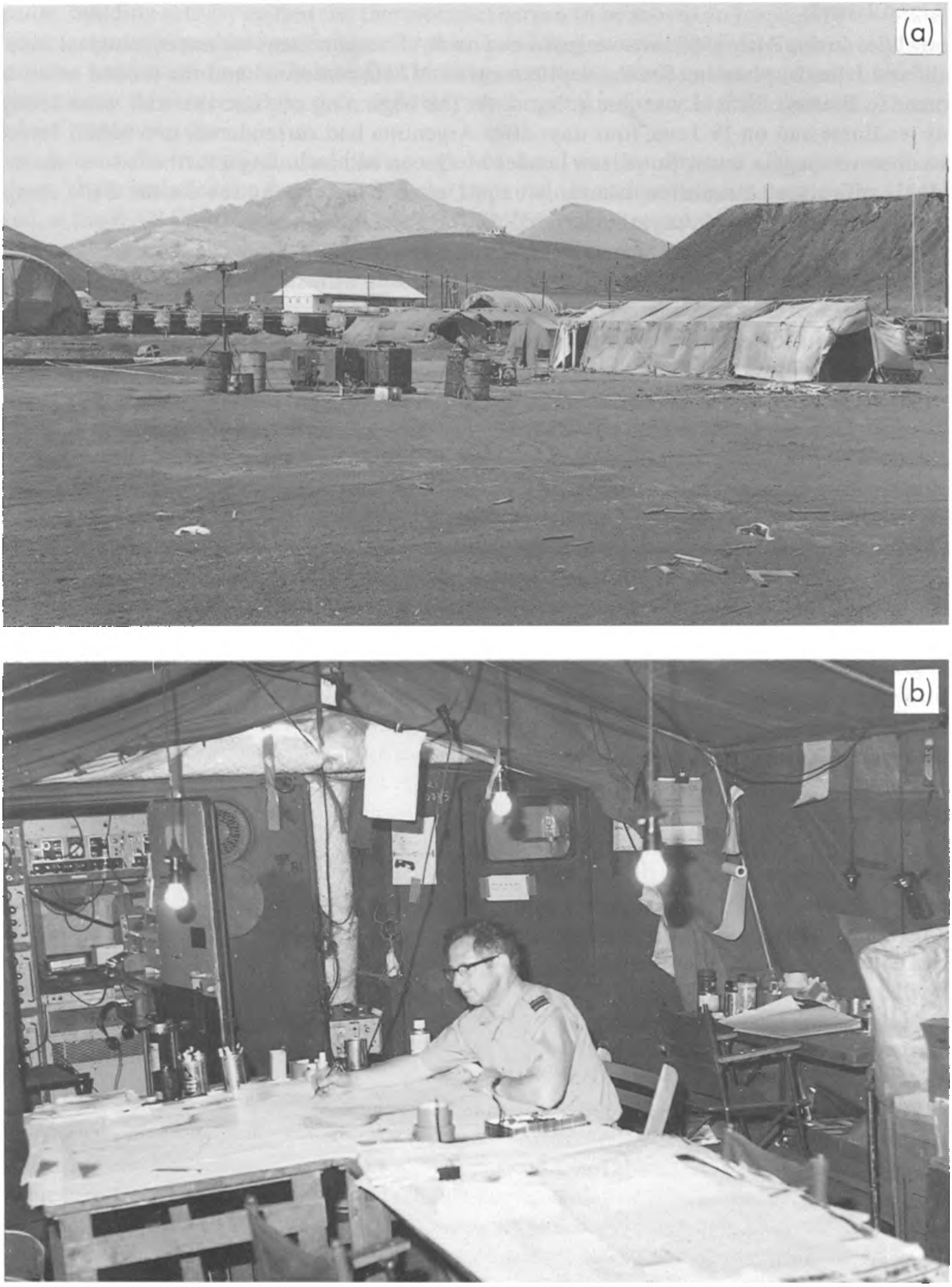
Figure 1. Map showing the position of the Falkland Islands and other places mentioned in the text.

some attention'. On 14 April two additional MMU officers were flown to Ascension Island but, owing to the severe shortage of accommodation on the Island at this time, one of these officers plus one of the original four was instructed to return immediately to the United Kingdom. The Unit strength thus remained at four and, although *roulements* (the rotation of military personnel/equipment) took place approximately every six weeks, it was to be August — nearly two months after Argentina had surrendered — before the strength of the detachment could be increased to five.

Nonetheless, with invaluable weather satellite imagery, improved reception of international meteorological radio telegraph and facsimile broadcasts and, from 17 April, forecasts of winds and temperatures at several upper levels from the Meteorological Office 15-level computer model (the southern hemisphere aspect of which had been subject to extensive programming work at very short notice), the MMU was able to meet the exacting demands placed upon it by RAF activity — particularly for air-to-air refuelling — in the North and South Atlantic as the Task Force moved southwards.

Following the recovery of the Falkland Islands, conditions at Ascension Island gradually improved. In June essential servicing of communication equipment was undertaken by staff from Bracknell. In July domestic accommodation was transferred to a bungalow in Georgetown and, although rooms were still shared, this was a great improvement. As mentioned earlier, in August the detachment strength was increased. Towards the end of the year additional furniture was received for the office and, finally, in March 1983 the MMU moved from its tented accommodation to an air-conditioned cabin. Throughout this period the routine had settled down mainly to forecasting for northbound flights to Dakar and the United Kingdom, and near-daily C130 flights and their supporting tanker aircraft to RAF Stanley.

During 1983 plans were made to transfer the RAF Ascension meteorological commitment from the MMU to normal civilian manning and, as mess accommodation became available at the new RAF complex at Travellers Hill, the change was gradually made between December 1983 and March 1984 — the last Ascension-based MMU officer arriving back in the United Kingdom on 28 March 1984.



Photographs by courtesy of Flight Lieutenant P. Wyatt (MMU)

Figure 2. The MMU tented office at Wideawake airfield, Ascension Island, (a) outside and (b) inside views.

3. Falkland Islands

Meanwhile, during May 1982, in anticipation of an RAF requirement for meteorological support in the Falkland Islands, planning for the deployment of MMU personnel and the second set of MMU equipment to Stanley airfield was put in hand. At the beginning of June the staff were brought to 48-hour readiness and on 19 June, four days after Argentina had surrendered, two MMU forecasters and two observers, again under Squadron Leader McQueen and including a further two of the original four MMU officers on Ascension Island, left the United Kingdom by sea on the TEV *Rangatira*. Twenty-two days later, on 11 July, they arrived off the Falkland Islands.

On 13 July, naturally believing themselves to be the first MMU personnel on the Falkland Islands, they set out to 'set up shop' on Stanley airfield. It was thus with some amazement (and not a little disappointment) that they were met on the airfield by a fellow MMU officer who, at very short notice to meet an urgent requirement for meteorological observations to support RAF operations at the airfield, had flown to RAF Stanley arriving on the 5th.

The appalling conditions obtaining at and around Stanley airfield were comprehensively covered by the media at the time. Suffice to say that with minefields everywhere, and unusually severe South Atlantic midwinter weather, any difficulties which had been encountered on Ascension Island soon paled into insignificance. Even with the MMU's well-known reputation for improvization and innovation, improvements were to be very slow.

The MMU was allocated a small room at the front on the ground floor of the airfield control tower (Fig. 3). Conditions were primitive. Apart from one table, furniture consisted of crates and boxes. Lighting was by one 60-watt bulb. All radio equipment was in the room, as was the weather satellite reception equipment. Administrative matters were also dealt with here. In such conditions the MMU officers grappled with southern hemisphere weather forecasting.

Photograph by courtesy of Mr E. Hibbett

Figure 3. Control tower, RAF Stanley, Falkland Islands. The weather satellite dish aerial can be seen on the ground (left) and the laser cloud-base recorder on the roof (right).

Outside, building activity caused the thermometer screen to be moved so frequently that, finally, the thermometers were placed in a marine screen which was hung on a nearby pole. Surface wind speed was measured by hand anemometer. In marginal landing conditions, an observer could be required to stand near the runway, whatever the weather, and relay readings by radio to air traffic control. There was no cloud-base measuring device.

Apart from radio reception, the other source of data was by directed signals from the United Kingdom. These included the Bracknell forecast upper winds for the South Atlantic. The signals were received, at the RAF Communications Centre (COMCEN) which was several hundred yards away, and had to be collected; additionally, all outgoing traffic — e.g. routine observations, airfield landing forecasts and aircraft debrief data — had to be taken to the COMCEN. When transport was not available this was a tiresome chore; at night, if contact with the patrolling guard dog handlers could not be made, the 'signals run' was even more unpopular.

Domestically, conditions were little better. Accommodation, two to four per cabin, remained on the TEV *Rangatira* which was moored in Stanley harbour. Travel to work comprised transfer from the ship by landing craft followed by a five-mile journey over pot-holed roads by truck to the airfield. Because both components of the journey were so unreliable, 24-hour duties were worked. The return journey for tired staff seemed even more unpleasant, especially as it was often 27 hours before staff were back on board the *Rangatira*. Even then, despite their extreme tiredness, frequent messages over the ship's tannoy system, military exercises, and the difficulties shift workers always experience when sharing accommodation, would often combine to make sleep difficult.

Apart from the air freighting to Stanley of an anemometer mast and its installation with its associated equipment, overall conditions for the MMU in the Falkland Islands during the ensuing months improved only marginally. The small size of the MMU and its concurrent commitment on Ascension Island dictated that Stanley *roulements* had to be by air from the United Kingdom — i.e. the Unit could not tolerate the time penalty of travel by sea between Ascension Island and the Falkland Islands. At the same time, pressure on air-bridge seats between Ascension Island and RAF Stanley resulted in detachments being set at three months. It is little wonder that the above regime, with some weeks in which more than 100 hours were worked, often led to officers returning to the United Kingdom visibly tired and drawn.

In May 1983, however, the situation began to improve with the servicing and upgrading of communications and other equipment by staff from Bracknell. (Meteorological Office technicians were subsequently to visit the South Atlantic offices at regular intervals.) During June and July domestic accommodation was transferred, at last, to one of the nearer floating accommodation units known as Coastels and towards the end of the year extra office accommodation became available in the control tower thus relieving the cramped conditions. A laser cloud-base recorder was received and was immediately made operational. Although a 'nodding beam' cloud-base recorder had been on the islands for many months, it had proved impossible to obtain the necessary priority for its installation. This was symptomatic of the frustrations experienced at the time.

There were setbacks, though. Despite strenuous efforts locally and in the United Kingdom, attempts to obtain a dedicated vehicle for the MMU were unsuccessful and the untold inconvenience and inefficiency this caused continued — as did reliance for transport on the enormous goodwill of air traffic control and operations staff. In June an officer on his second tour of duty at RAF Stanley broke his wrist while observing in gale force winds from the ice-covered aircraft dispersal area and was casualty evacuated.

In addition to its basic role of providing continuous observations, forecasts for local military operations, and route forecasts, the MMU undertook other tasks. These included the installation of meteorological instruments, and the training in weather observing of Service personnel at remote exposed sites and of Army personnel *en route* to South Georgia. By now, the decision had been taken to construct a major airfield at Mount Pleasant. The MMU helped the Property Services Agency (PSA) to set up a rudimentary observations programme there and, later, the MMU became increasingly involved 'on the spot' as the planned Main Meteorological Office (MMO) at Mount Pleasant took shape.

Further changes and improvements occurred during 1984 and 1985. In July 1984 the MMU at last received its own vehicle. That November a satellite telegraph link from Bracknell into the Stanley office became operational and eliminated the requirement for directed signals and the routine reception of radio telegraph broadcasts. Meteorological bulletins originating in the United Kingdom or taken from the Global Telecommunication System were automatically routed on to the link. In February 1985 a facility to send messages to Bracknell for automatic handling also became operational. In April responsibility for forecasting for the Falkland Islands Protection Zone was transferred to the MMU from the Royal Navy and on 1 May 1985, when RAF Mount Pleasant became partially operational, the MMU became responsible for its landing forecasts, weather warnings and route forecasts. Indeed, when the first wide-bodied aircraft landed at Mount Pleasant on that day, the captain congratulated the MMU on an excellent landing forecast — the weather improving, as forecast, shortly before the aircraft landed. *Roulements* were now by British Airways 747s or RAF Tristars in and out of RAF Mount Pleasant; this was a considerable improvement on the air-bridge flights.

A civilian Meteorological Office observer had been posted to RAF Mount Pleasant for the initial operations and worked from temporary accommodation. During the rest of 1985 the observing programme and staff there gradually increased. At the end of 1985 the MMO building was formally accepted by PSA from the contractors, and between February and April 1986 the MMO built up to its full complement. At the end of April, as the RAF transferred its operations from RAF Stanley to RAF Mount Pleasant, the MMO, under a Principal Meteorological Officer, accepted full responsibility for all the MMU's functions at RAF Stanley and the MMU was simultaneously withdrawn.

Thus ended almost exactly four years of MMU operations in the South Atlantic.

4. Commentary

The greatest strain upon the MMU was from July 1982 to the end of 1983 when, within its original complement, the Unit was operational at both South Atlantic locations. During this period officers could expect less than a month in the United Kingdom between detachments. In November 1983 the MMU ceiling was increased to 25. Although this ceiling was never to be quite reached, further volunteers into the MMU, combined with the civilianization of Ascension Island by March 1984, sharply reduced the burden. Nevertheless, 5 officers each completed no less than 9 tours of duty in the South Atlantic and a further 12 officers each completed 6 or more tours.

By 1982 the long-term future of the MMU had been uncertain for some years and for this reason it had not been possible for resources to be allocated for updating equipment. When the call came in 1982 the MMU radio communications and weather satellite reception equipment were antiquated — the radio equipment had valves! The continuous operation of such equipment in poor conditions resulted in considerable maintenance problems. That these difficulties were largely overcome, frequently by the exchange of numerous signal messages, reflects the considerable efforts and expertise of the Meteorological Office Telecommunications Branch at Bracknell and the MMU personnel and RAF technicians on the spot.

In addition to the essential support received from the Telecommunications Branch, the MMU also acknowledges the support it received from the Directorate of Naval Oceanography and Meteorology, from the Principal Forecasting Office, Headquarters Strike Command, and from a number of Headquarters Branches at Bracknell. These include, in particular, the Special Investigations Branch

(which not only put together within days in April 1982 a South Atlantic climate brief but subsequently actioned, at short notice, many requests for statistical data in the South Atlantic region), the Central Forecasting Branch, and the equipment section of the Finance and Supply Branch.

5. Awards and appreciations

Following Operation Corporate, Squadron Leader McQueen was awarded the MBE and ten members of the MMU were awarded the South Atlantic Medal. The invaluable service provided by the MMU, both during Operation Corporate and afterwards, has been recognized in many quarters, and messages of appreciation have been received from the Air Staff, the senior Directorate of the Meteorological Office and the Director of Naval Oceanography and Meteorology. Most recently, Air Vice-Marshal K.F. Sanderson, CB, RAF, Air Officer Commanding Directly Administered Units, Headquarters RAF Strike Command, paid tribute to the MMU, complimenting the officers on their enormous contribution to RAF operations in the South Atlantic, their dedication to duty during frequent tours often in poor living and working conditions, and noting that, for many, this had meant a great deal of separation from their families. The Unit itself is listed on the Falkland Islands War Monument together with the other branches of the RAF which took part in the Falklands Campaign (Fig. 4).

Figure 4. Falkland Islands War Monument, Port Stanley. *Photograph by courtesy of Mr E. Hibbett*

6. Acknowledgement

The writer gratefully acknowledges receipt of a lengthy note on the MMU prepared in August 1985 by the late Wing Commander Max Lloyd, OCMMU.

551.5:06.09

Irish Meteorological Service jubilee

By F.E. Dixon*

Summary

Nineteen eighty-six is the jubilee of the Irish Meteorological Service. This is therefore an appropriate time to describe the establishment of the Service and the way it has developed during the last 50 years.

When the Meteorological Office was established in 1867, and for long afterwards, until the development of radio, Ireland was of exceptional importance. The telegraphic reporting station at Valentia Observatory (at one time called the Western Observatory) gave the first indications of each successive new weather system approaching Europe from the Atlantic. R.H. Scott, the first Director of the Meteorological Office, had a particular interest in Ireland, being a native of Dublin, and for many years he personally carried out the annual inspections of the Irish stations.

The establishment of the Irish Free State in 1922 had little effect on meteorological matters, newspaper forecasts still being supplied from London and the observing stations of all kinds being controlled by the Meteorological Office. It was transatlantic flying which brought about a change: an Irish Trans-Atlantic Corporation originated as early as 1931 and it was formally incorporated in Ireland in the following year, and registered in London in 1935. At an Ottawa conference in November 1935 to work out detailed arrangements the Irish Free State committed itself, *inter alia*, to establish a Meteorological Service and the UK Government undertook to contribute £6000 a year for it and the other facilities.

There was no delay in the inauguration of the new Service with the appointment of Austin H. Nagle as first Director, in 1936, with a good Irish name and several years' experience in the Meteorological Office. At first he had only clerical staff, but another Irishman was found, S.G.G. Kelliher, recently retired from the Colonial Service, who was at first put in charge of Valentia Observatory. He later proved to be the ideal man to visit voluntary climatological stations and persuade the observers to transfer their allegiance to the Free State. No other professional staff were appointed until 1939, and for the flights in 1937 and 1938 forecasters were seconded from the Meteorological Office, with S.P. Peters in charge at the new flying-boat base in Foynes. The men appointed in 1939 included seven potential forecasters (four Irish, two English, one Welsh) and Mr Nagle organized a thorough training course for them at the Imperial College, London, under Professor D. Brunt. World War II brought this to a premature close, and the training was finished in Foynes under Professor L.W. Pollak, a Czech refugee. It was fascinating to discover that in World War I he had served on the Austrian front opposite S.P. Peters and had been able to break the code and make use of Peters's pilot balloon reports! Little has been revealed about the co-operation of the neutral Irish Free State and the belligerent United Kingdom but J.M. Stagg disclosed in his account of the D-day forecasts that a report from Blacksod was crucial in deciding which team of forecasters had the right analysis.

When R.H. Scott died in 1916 his executors put most of his library at the disposal of the Meteorological Office, and they placed it in the Valentia Observatory. When the Irish Meteorological Service came into being the Meteorological Office generously allowed this Scott library to remain intact, and also sent surplus and duplicate volumes to assist in establishing a library in the new headquarters in Dublin. The Royal Meteorological Society also gave valuable additions.

* Formerly of the Irish Meteorological Service.

The headquarters had been moved twice in the 50 years, from 14/15 St Andrew Street, Dublin, to 44 Upper O'Connell Street, and now to a modern specially designed building at Glasnevin, a northern suburb. Aviation forecasting is now only a small part of the output of the Service, and every application of meteorology is dealt with — agriculture, shipping, industry, etc.

The Irish Meteorological Service is an offspring of the Meteorological Office, and both parent and child can be proud of the developments of the last 50 years.

Conference report

The Sixth Conference on Atmospheric Radiation of the American Meteorological Society, Williamsburg, Virginia, 13–16 May, 1986

The conference was held concurrently with the Second Conference on Satellite Meteorology/Remote Sensing and Applications and consisted of eight sessions plus two joint sessions. The first session, on Aerosols and Radiation, started with an invigorating paper from C.F.Bohren (Pennsylvania State University) emphasizing the need for more advanced treatment of the extinction of light by non-spherical particles than the widely used approximation of Mie theory using equivalent spheres. This session also included discussion of the 'nuclear winter' with some attention being paid to the properties of combustion-produced aerosols. A paper describing the results of a flight made by the Hercules aircraft of the Meteorological Research Flight during a straw-burning episode was of interest in this regard.

The second session, Clouds and Radiation, contained papers aimed at the two phases of FIRE (First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment) in 1987 and 1988 looking at the properties of cirrus and stratocumulus. This was followed by a poster session dealing with radiation instrumentation, including ground, airborne and satellite instruments, illustrating well the increased interest and effort in this area.

Two sessions were then held jointly with the satellite conference. The first reported the objectives, performance and initial results of ERBE — the Earth Radiation Budget Experiment now flying on the ERBS and NOAA-9 satellites. The systems are working well and a high-quality global data set of great potential value to many atmospheric scientists is emerging. A subsidiary measurement from a solar monitor implied that the solar constant has been close to 1365 W m^{-2} for the last six months. The second joint session reported results from SAGE II (the Stratospheric Aerosol and Gas Experiment), flying on board ERBS, launched in 1984. Profiles of aerosol, ozone, nitrogen dioxide and water vapour have been collated for over a year now, and all objectives appear to have been achieved.

The fourth and fifth sessions of the radiation conference covered the remote sensing of clouds, aerosols and temperature, with a variety of sensors — airborne lidar and radiometers AVHRR/2 and HIRS2/MSU. Contributions included observations of the El Chichon stratospheric aerosol and satellite observations of the smoke from a large Canadian forest fire.

The next session, Spectroscopy and Band Models, contained two invited papers on the infra-red absorption spectrum of water vapour. In particular, these showed that the cause of the continuum absorption in the atmospheric window at 8–13 μm had not yet been resolved, although evidence now favoured accumulated absorption by the far wings of water vapour lines, rather than absorption by aggregates of two or more molecules of water vapour, neither cause could be ruled out. Band models have been developed to such a degree that they can now be compared with line-by-line models, but it was reiterated that atmospheric measurements, both broad band and high resolution, are required in order to verify the line-by-line models.

In the seventh session, Radiative Transfer, several theoretical studies of 'realistic' atmospheres were presented, including one based on the application of the principle of fractal dimensions (after Mandelbrot) to a study of the effect on radiative transfer of microscale inhomogeneities of liquid water content in layer and broken cloud. The conference closed with a session entitled Earth Radiation Budget and Climate Applications, containing work on the Nimbus-7 Earth Radiation Budget climate data set as well as other aspects of the global radiative balance.

The general view emerging from the conference was that modelling had to some extent outrun the observational data, and that there was a pressing need for further airborne and satellite measurements of radiative transfer. Further details about the papers presented can be found in the proceedings which were published before the conference began.

C.G. Kilsby

Review

Reviews of United Kingdom statistical sources, Volume XVII: Weather, by B.W. Atkinson, *and Water,* by E.C. Penning-Rowsell and D.J. Parker, 170 mm × 250 mm, pp. 226, *illus.* Pergamon Press, Oxford. Price £27.00, US $35.00.

This book forms part of a series under the general title *Reviews of United Kingdom statistical sources* that covers topics as diverse as 'Crime' and 'Civil aviation'. The primary aims of the series are to enable the user to find out what sources of statistical data are available, where the data may be obtained and what limitations there are to their use. The authors of the two reviews in this volume achieve this aim. Available data refer only to those which are likely to be released to a bona fide enquirer in any format.

Extremely useful features of the reviews are the references. Each review contains a quick reference list (QRL) of data publications ordered by content, a QRL of the same publications by author or organization and a general bibliography of works discussing wider aspects. The reader is constantly referred to these in each text but unfortunately there are a number of errors that often direct one to the wrong reference. There is also a subject index on textual references in which entries are permuted.

The text of each topic is designed, in so far as the varying subject matter will allow, to follow a standard format so that users can expect a similar pattern throughout the series. This is certainly the case for *Weather* but less so for *Water* though familiarity with the one helps facilitate the use of the other. Both reviews start with a brief summary of the topic covering such aspects as its organization, the measurements (stating when and how they are made), the units used, the reporting channels and where the data are processed. Each then goes on to discuss the various types of data in detail.

Weather starts with a potted history of observing and instruments, and goes on to describe the various types of observations and networks. The distinctions between synoptic and climatological networks and observations are not made perfectly clear, but the text does contain all the relevant information. The chapter closes with a paragraph on the nature and form of the data.

The second chapter gives the sources of surface data. The variables covered are climate, weather, sunshine, radiation, temperature, evaporation and evapotranspiration, visibility, pressure, and cloud. A standard form is followed with paragraphs on how the measurements are made — data in research literature, published data, and unpublished data both non-machinable and machinable. The definition of radiation reads as though the pre-existence of electric and magnetic fields is necessary for the propogation of radiation, but this apart it is all relatively straightforward and the author refers to all the major sources of data.

Chapter three covers upper-air data. Radiosonde data are in the same form as described above but radar and satellite data are more descriptive and give only general works as data sources. The final chapter is entitled 'Improvements and future developments' and some of the developments discussed have already taken place (the review was written in 1982). Hence, the introduction of the new common code has seen the end of some returns and a greater usage of the computer as an archive which, as the author points out, is not always the boon it may seem for the potential user. Of the criticisms levelled at the Meteorological Office the major one is the fact that one single comprehensive volume of data sources did not exist before this review was written. It is restricted to national data and anyone seeking more detailed local information will need to contact the National Meteorological Library.

Prof. B.W. Atkinson is at least fortunate in the respect that the bulk of weather data are located under one roof and that standards and formats are generally consistent. Dr E.C. Penning-Rowsell and Dr D.J. Parker, the authors of *Weather*, are faced with a water industry that has gone through a number of reorganizations in the last 35 years, and with each change there has been a like change in the nature and extent of published data. Consequently much of the data described are of recent origin and of an uneven and varied nature both spatially and temporally. Nevertheless, the authors manage to present a lucid account of a patchwork quilt of data.

After the brief introduction, data sources and institutional arrangements are discussed giving information on the structure of the Water Authorities in England and Wales and the Scottish River Purification Boards, followed by a section on financial aspects and manning and performance ratios. Subsequent chapters give information on supply, pollution and related statistics, recreation and amenity statistics, and flood alleviation. The varied nature of the data sources precludes a consistent form.

The final chapter is entitled 'Evaluation' and it is worth quoting the closing paragraph more or less verbatim '... nevertheless it will be apparent ... that taken as a whole the data series on the water services in the UK are both chaotic and inaccessible. They pose innumerable problems for the researcher attempting more than a superficial analysis of spatial and temporal trends. In addition it should be stressed that the accuracy and appropriateness of the data may well be less than it appears, not least owing to irregular and inconsistent sampling, and that a most careful evaluation is necessary of any data used'. *Water* was written in 1983 and since then the Government has announced its intention to privatize the water industry and who knows what changes this will effect.

This volume will provide any user with a quick and easy reference to the major national sources of data for both topics but no more than this. At £27.00 it is not destined to become a best seller but should prove a useful addition to any reference library.

R.D. Whyman

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

Fields, currents and aerosols in the lower troposphere, by R. Reiter (Rotterdam, A.A. Balkema, 1986. £29.75) is the result of a spontaneous attempt to compile the results of ten years of intensive research concerned almost exclusively with atmospheric electricity and radioactivity. The idea was to bring forth the mutual relationships between all separate findings of research in diverse fields. All these results still hold good and have been repeatedly confirmed. In this revised and enlarged edition the recent literature in the individual fields of research has been added at the end of certain chapters and some important new findings reported.

Structure and variability of the Antarctic Circumpolar Current, by E'. I. Sarukhanyan (Rotterdam, A.A. Balkema, 1986. £19.00) describes the salient features of the spatial structure of the Antarctic Circumpolar Current (ACC) based on the analysis of long-term observations on the current. These observations were made during 1975–79 in different regions of the Southern Ocean, in the course of the large-scale field experiments under the 'POLEX-South' and 'International Research Studies on Southern Ocean' programs. The geostrophic transport of waters in the ACC system has been evaluated. Basic scales of the tidal, inertial and synoptic oscillations of the current velocities have been established.

The Bunker climate atlas of the North Atlantic Ocean, Volume 1: Observations, by H.-J. Isemer and L. Hasse (Berlin, Heidelberg, New York, Tokyo, Springer-Verlag, 1986. DM 275) is based on data originally evaluated by Andrew F. Bunker of Woods Hole Oceanographic Institute. It deals with the surface climate of the North Atlantic Ocean from the equator to 65° N, in the period from 1941 to 1972. By the use of monthly and annual mean charts and other diagrams the annual cycles of various oceanic and atmospheric surface parameters are presented. Volume 1 contains the observed meteorological quantities. For the most part they represent the basic information required to understand Volume 2, which presents derived parameters such as energy budget terms and ocean transports.

Honour

We would like to congratulate Mr J. Findlater on his award of the Imperial Service Order in the Queen's Birthday Honours List. Mr Findlater recently retired from the Meteorological Office, Bracknell as a Principal Scientific Officer in the Special Investigations Branch. During his distinguished career in synoptic meteorology he gained international recognition for his discovery in the mid-1960s of the East African jet (sometimes referred to as the Findlater jet) when he was forecasting at RAF Nairobi. During a further tour in East Africa in the 1970s he took a leading role in planning investigations of the jet during the Monsoon 77 and MONEX experiments, and in aircraft studies of its structure.

Award

The President and the Council of the Royal Society have announced that the Royal Society ESSO Energy Award for 1986 will be made to Dr P.W. White, Dr M.J.P. Cullen, Dr A.J. Gadd, Mr C.R. Flood, Mr T.N. Palmer, Mr K. Pollard and Dr G. Shutts of the Meteorological Office, Bracknell for work on the development and introduction of a global weather forecasting system that provides accurate forecasts of wind and temperature for the civil aviation industry, by which aircraft routes are selected to make maximum use of the prevailing winds resulting in considerable fuel savings.

The Award, which was instituted in 1974 and is provided by a gift to the Royal Society from the Board of Directors of the Esso Petroleum Company (now ESSO U.K. plc), consists of a gold medal and a prize of £2000. It is made annually to a person or team who, in the opinion of the Council of the Royal Society, has made an outstanding contribution to the advancement of science or technology leading to the more efficient mobilization, use or conservation of energy resources.

The Award will be presented at a special meeting of the Royal Society on the evening of Monday 13 October 1986 at which Dr White will give a lecture about the work.

Meteorological Magazine

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe the results of research in applied meteorology or the development of practical forecasting techniques.

Preparation and submission of articles

Articles for publication and all other communications for the Editor should be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ and marked 'For *Meteorological Magazine*'.

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately.

Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

References should be made using the Harvard system (author, date) and full details should be given at the end of the text. If a document referred to is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to.

Tables should be numbered using roman numerals and provided with headings. We consider vertical and horizontal rules to be unnecessary in a well-designed table; spaces should be used instead.

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and difficult to read. Keep notation as simple as possible; this makes typesetting quicker and therefore cheaper, and reduces the possibility of error. Further guidance is given in BS1991: Part 1: 1976 and *Quantities, Units and Symbols* published by the Royal Society.

Illustrations

Diagrams must be supplied either drawn to professional standards or drawn clearly, preferably in ink. They should be about 1½ to 3 times the final printed size and should not contain any unnecessary or irrelevant details. Any symbols and lettering must be large enough to remain legible after reduction. Explanatory text should not appear on the diagram itself but in the caption. Captions should be typed on a separate sheet of paper and should, as far as possible, explain the meanings of the diagrams without the reader having to refer to the text.

Sharp monochrome photographs on glossy paper are preferred: colour prints are acceptable but the use of colour within the magazine is at the Editor's discretion. In either case contrast should be sufficient to ensure satisfactory reproduction.

Units

SI units, or units approved by WMO, should be used.

Copyright

Authors wishing to retain copyright for themselves or for their sponsors should inform the Editor when they submit contributions which will otherwise become UK Crown copyright by right of first publication.

It is the responsibility of authors to obtain clearance for any copyright material they wish to use before submitting it for publication.

Free copies

Three free copies of the magazine are provided for authors of articles published in it. Separate offprints for each article are not provided.

Meteorological Magazine

August 1986

Vol. 115
No. 1369

CONTENTS

Contributions: it is requested that all communications to the Editor and books for review be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, and marked 'For *Meteorological Magazine*'. Contributors are asked to comply with the guidelines given in the *Guide to authors* which appears on the inside back cover. The responsibility for facts and opinions expressed in the signed articles and letters published in *Meteorological Magazine* rests with their respective authors. Authors wishing to retain copyright for themselves or for their sponsors should inform the Editor when submitting contributions which will otherwise become UK Crown copyright by right of first publication.

Subscriptions: Annual subscription £27.00 including postage; individual copies £2.30 including postage. Applications for postal subscriptions should be made to HMSO, PO Box 276, London SW8 5DT; subscription enquiries 01–211 8667.

Back numbers: Full-size reprints of Vols 1–75 (1866–1940) are available from Johnson Reprint Co. Ltd, 24–28 Oval Road, London NW1 7DX. Complete volumes of *Meteorological Magazine* commencing with volume 54 are available on microfilm from University Microfilms International, 18 Bedford Row, London WC1R 4EJ. Information on microfiche issues is available from Kraus Microfiche, Rte 100, Milwood, NY 10546, USA.

ISBN 0 11 727836 X

ISSN 0026–1149

Printed for HER MAJESTY'S STATIONERY OFFICE
by Delco Printing Co Ltd 8/86 Dd. 739131 C13