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Met.O.915

METEOROLOGICAL OFFICE

the meteorological magazine

JANUARY 1978 No 1266 Vol 107
Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.915

THE METEOROLOGICAL MAGAZINE

No. 1266, January, 1978, Vol. 107

551.578.42(411):551.578.46

VARIATION IN THE FREQUENCY OF SNOWFALL IN EAST-CENTRAL SCOTLAND, 1708–1975

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SUMMARY

For east-central Scotland records can be assembled of the number of days with snow or sleet observed to have fallen since 1754, with a reasonable extension back to 1708, by using a wide variety of sources from coastal Aberdeenshire to Pennine Yorkshire. From 1876 some official stations become available. Perfection in recording snow or sleet is infrequently attained; eye observation may be maintained throughout the 24 hours but in general is not. Attention paid to brief passing showers or rainy sleet can be shown to vary even among records from climatological stations; comparison is complicated by altitude, aspect, and distance from the sea. Station records can be broadly classified under four headings, the highest being that of official observatories and major operational airfields. The ratio between these categories is discussed; although routine observations by non-meteorological personnel commonly give much lower totals they remain in general consistent and useful. For the numerous stations, largely amateur, kept before 1880 allowances can be made based on inspection and comparison of original records. Sources are listed with estimates of class; conversion factors are given; annual totals at several stations are shown for comparison, those before 1770 being less certain. References are given to numerous little-known or neglected Scottish sources, some recently found. Results are shown in relation to the 1941–75 average; since 1876 they range from 0·4 (1957, 1959) to 2·1 (1879). The 1780s stand out, the 1880s less so.

INTRODUCTORY

Eighty years have elapsed since Mossman (1896, 1897a) produced his compilation of the Edinburgh observations since 1731, on which many have relied when seeking an index of past vicissitudes representative of Scotland. His massive papers followed earlier assemblages by Forbes and Buchan. Much can now be added; more early sources have been found, and we know more about the problems of assembly. The purpose of this paper is to assemble, standardize and discuss the available material with regard to the number of days on which snow or sleet have been observed and recorded as falling. The fact that beside Edinburgh the annual average at Turnhouse Airfield since its record began in 1949 is 31 while that at the Royal Observatory on Blackford Hill is 20 attracts immediate attention; what are future compilers to do when they set out to investigate variability if they are confronted by such results from two adjacent institutions of scientific repute? It will be demonstrated that both records can be reconciled, have value, and can be used.

It is everywhere evident that under existing rules the results of eye observations of this element differ considerably, even at adjacent stations at which we have no meteorological reason to suppose that there should be any serious or systematic difference in the annual totals. This is understandable; at the climatological stations that provide the majority, observers differ in age, scientific proclivities, the amount of attention they can pay to events out-of-doors, the number of hours on duty and interest in what happens outside these hours. Quite often they reside at some distance; moreover they must be expected to pass upwards of a quarter of their time asleep. The resultant differences, for North Wales and adjacent counties were discussed by Ashmore (1952), who concluded that four or possibly five types of station could be recognized. The present author (Manley, 1958) considered the observations at the stations around London and the Home Counties and showed that Ashmore's categories could be applied very well in that region; moreover, adjustments for altitude could be devised with the aid of such records as those from Croydon, Biggin Hill and Little Rissington among the airfields, or Hampstead, Rothamsted and Whipsnade among the climatological stations.

In an earlier paper (Manley, 1940) based on observations from 1912 to 1938 over the British Isles, when there were few operational airfields, it was necessary to draw up the map of annual averages of 'days with snow' on the basis of 'good climatological standards'. These are still effective for most working purposes and can continue to provide, as at Blackford Hill, a useful picture of distribution and reasonable standards of comparison. But now that we have a widespread network of airfields at which professional observers keep, in general, a constant watch and for obvious reasons are alert to the first appearance of small amounts of sleet in cold rain, or those brief flights of snowflakes that so often drift down on the margin of an anticyclone, especially in eastern Britain, we can make comparisons and allowances for differing types of station in many districts, for example around Manchester. In particular, we can examine and compare the totals at numerous stations in eastern and central Scotland in considerable detail. We have upwards of 25 years from Leuchars and Turnhouse, with other airfields similarly exposed at no great distance, with a similar expectation of the incidence of those airstreams and synoptic situations likely to provide air cold enough for sleet, at least, to be observed down to sea level. Accordingly we can consider Acklington, Leeming, Dishforth and Dyce. Inland at a higher altitude Eskdalemuir Observatory, like Kew and Lerwick, can also be expected to provide 'first-class' observations. Prestwick and Abbotsinch demonstrate the result of being situated on the more sheltered western side of Scotland.

We can illustrate these trends by setting out for comparison the averages for 1961–75 at a selection of lowland stations (below 200 feet) around Edinburgh and across to the Tay, the number of days being rounded to whole numbers for convenience.

A. Turnhouse 34, Leuchars 34 (Acklington 36, Dishforth–Leeming 34 approx.)
B. Pitreavie 25, Montrose 27 (Tynemouth 30).
C. East Craigs 20, Haddington 21, Dundee 22, Perth est. 21, Carnoustie est. 20, Kirkcaldy 20.
D. Botanic Gardens 17, Dunbar 15, Arbroath 13, St Andrews est. 16.

Some comparable figures can be added here, taken from the old *Book of Normals* (1881–1915) for periods between 1876 and 1920.

Aberdeen (Obsy) 34.0, Dundee 25.1, Leith 17.2, Shields 22.6, Sunderland 27.9, also Glasgow (Obsy) 16.5. (Durham (Obsy) 1881–1920, 33.1, can be added from the MS. record.,

For 'Edinburgh' the 1881–1915 average is (approximately) 22, based on three stations in extension of Mossman's series. The low figures at Leith (a 'telegraphic' station) and Glasgow (Obsy) are noteworthy.

In broad terms we can recognize here a group (A) of active airfields; (B) a few exceptional climatological stations, such as are sometimes maintained under the auspices of universities or professional engineers, but which are not likely to be alert through the night, while (C) and (D) form the majority of the climatological stations. Some of the (C) stations, typified by the agricultural institutes with an obvious interest in weather, have resident staff who have reason to be observant, and may visit instruments twice daily, whereas (D) include many at which instruments are visited once daily, and while such stations can provide very consistent observations over long periods, these observations are likely to be made by staff who have other duties during the working day, and who subsequently depart to reside at some distance. It is clearly not possible to make a precise distinction between (B), (C) and (D); but if for any one station the annual totals are entered beside those of one or more adjacent stations the effect of a change in the observational routine can generally be seen at once. For example, compare for 1925–50 the following:

Leuchars 22.2, Perth 21.6, Dundee 17.9, Arbroath 16.1.

But for 1951–70 we have Leuchars 32.2, Perth 23.5, Dundee 23.7 and Arbroath 16.3. From 1955 onwards Leuchars agrees closely with Turnhouse. 'Amateur' stations are now very few; they may fall into any class, as was demonstrated by the older West Linton observations at the station established early in this century by the Revd J. Begg, a well-known member of the Scottish Meteorological Society before its amalgamation with the Royal Meteorological Society in 1921. Near London, the late E. L. Hawke likewise recorded nearly twice as many days with snow as did observers at some neighbouring stations.

In colloquial terms, we find the climatological stations which can be presumed to record 'conspicuous snow or sleet during the working day' (D); some would add to that 'noticeable snow' (C); some might be considered as 'careful observation throughout waking hours' (B), and at the active airfields 'meticulous observation throughout the 24 hours', or nearly so (A). In the minds of the non-meteorological public (D) may well be representative. Ashmore in his original paper provided a series of equations relating these categories; an 'A' station should be expected to give one-and-a-quarter times the average given by a 'C' station, plus five days. Scotland tends to have slightly more in the way of passing showers and it might be expected that the difference between 'A' and 'C' averages would be a little greater. I have accordingly taken out a number of comparisons among the available Scottish and northern English stations from which it seems reasonable to modify Ashmore's relationships as follows:

$A = 1{\cdot}1\ B + 4 = 1{\cdot}3\ C + 6 = 1{\cdot}5\ D + 8.$

This means that in the north an operational airfield will commonly average about twice the total given by routine climatological stations at the same level.

The rate of increase with altitude, about 1·5 days/100 feet for 'A' stations in southern England and 1.0 for the climatological stations, increases through northern England and southern Scotland to the central Highlands; in southern Scotland it appears to average fully twice that applicable in the south. For example over the period 1961–75, averages close to 20 prevail on the low-lying land round Edinburgh, 35 to 45 at 700–800 feet (Blyth Bridge, Carnwath, Stanhope Farm) and 50 at Leadhills (1270 feet) among the climatological stations, which works out at between 2 and 3 days for each hundred feet, but it is a little difficult to discount the possible consequences of conditional instability in the region of the Lammermuirs and Pentlands. To quote some of the averages for 1961–75 we have, from this area:

Blyth Bridge (830 ft) 44, Carnwath (706 ft) 42, Stanhope Farm (741 ft) 34, West Linton (800 ft) 28, Penicuik (620 ft) 33, Bush House (605 ft) 24, Blackford Hill (441 ft) approx. 21, but including 5 estimated years. The older stations on the upland outskirts of Edinburgh (Bangour, Boghall, Balerno) show similar differences.

THE EARLIER OBSERVATIONS

Decision with regard to the several categories of observation and entry of snow days must largely be a matter of judgement based on careful review of the appearance of the original entries and comparisons of the available totals. This applies to all the earlier observations, whose provenance will now be discussed.

Daily observations at stations under the control of the Scottish Meteorological Society, e.g. Braemar, were first organized in 1856, but 'days with snow' were not separately totalled until 1903. For a few 'telegraphic' stations (e.g. Aberdeen, Shields) and some second-order (e.g. Dundee) stations under the Meteorological Office, totals of days with snow are available from 1876 or soon afterwards, and in northern England the Royal Meteorological Society's second-order stations provide totals from 1874 onwards. Before this time it is necessary to search the MSS. or contemporary printed sources, and in many cases to count up the entries for each month; sometimes this gives an opportunity to estimate the observer's characteristics. For example the MS. (1771–81) of George Watson of Fiddes, a farmer close to the shore at Foveran, a few miles north of Aberdeen, soon gives the impression that he did not record snow on many of those days, so common along that coast, with passing showers of sleety rain on a raw easterly wind which but a short distance inland would fall as wet snow and might even provide a cover. Even today the differences between Mannofield, Craibstone and Dyce are very evident, more than is readily attributed to difference of level.

Mossman's massive assemblage for Edinburgh, already referred to, provides an overall average of 21 days with snow from 1771 to 1895; this happens to be remarkably similar to that of the climatological record maintained at the Royal Observatory on Blackford Hill (1903–67, 21 days). But Mossman does not appear to have been particularly critical of the snow observations, as may be judged from the comments on his paper on the London snow observations from 1713 onwards (Mossman, 1897b). Those which he assembled from a varied succession of Edinburgh observers clearly differed considerably in 'character of observations'. In the tabulation below we note some very low annual totals during the 1850s, a period when the Edinburgh observations depended on brief newspaper reports published from Adie's shop in Princes Street and, later on, on the observations made by a detachment of Royal Engineers engaged on the Ordnance Survey.

In order to overcome these difficulties I have collected and tabulated other series of annual totals, several from manuscript sources hitherto unused. Moreover, Scotland is rather short of snowfall observations between 1845 and 1875, unless we go as far north as Culloden (Arthur Forbes series, 1841–80); hence I have made use of records from the adjacent north of England (Newcastle upon Tyne 1802–33, Durham University Observatory 1848–1950, Sunderland 1857–1913 and Kendal 1830–70, together with a very good daily record from the flanks of the Pennines at Braithwaite above Keighley 1807–57). These assist the linkage of the earlier nineteenth-century Scottish records, e.g. Aberdeen 1799–1810, 1829–41; Perthshire 1804–32, 1865–74. In the *Journal of the Scottish Meteorological Society* for 1878 there is a summary of a Cruickshank record at Aberdeen, 1857–77, hard to interpret as he counts 'snow' and 'sleet' totals separately and they overlap; I have not yet found his original MS. For the later 18th century we have a recently discovered MS. meteorological journal, of very good quality, from Belmont Castle near Meigle in east Perthshire (1771–99) as well as the above-mentioned Foveran journal and that kept at Mause, north of Blairgowrie, 1754–74. I have also included totals (1785–1809) from the excellent record kept further west at Cambuslang near Glasgow. These are all in addition to the well-known Gordon Castle record (1781–1827) discussed by Buchan (1880) from further north in Moray, and they lie nearer to the Forth–Tay region in which we are primarily interested. Too much weight should not be given to observations from north of Aberdeen and the main Grampian watershed, and some brief earlier records at Aberdeen (1767–70), Selkirk (1768–70) and Kirkcaldy (1775–78) have for various reasons been omitted, while Rothesay (1818–30) lies too far west, and Carbeth Guthrie (1817–59) does not include snow.

Before 1754 daily observations are scarcely to be found in Scotland, despite considerable search. From the brief Edinburgh series used by Mossman (1731–36) it looks as if the daily entries merely refer to the weather at the time of observation. A little use can be made of Daniel Hasting's interrupted MS. record at Alnwick in Northumberland (1739–46). There are also the MS. weekly reports (1749–60) sent by the Earl of Bute's head gardener, Alexander McGrigor, from Mountstuart near Rothesay, but these are not sufficiently detailed to provide a good count of 'snow-days'. Hence one must again make use of Yorkshire journals from the flanks of the Pennines; notably, a recently discovered MS. for the neighbourhood of Dewsbury (William Elmsall, 1708–40) and Dr Thomas Short's MS. for Sheffield, 1734–55, together with Dr Nettleton's short series at Halifax, 1724–27.

That there is broad agreement between the fluctuations in Pennine Yorkshire and east–central Scotland, given the provenance of most of our snow on winds with an easterly component, can readily be demonstrated. In a simple form it appears in the diagram showing, in regard to frequency of snow, the general correspondence between the decadal running means from London through the Midlands and Edinburgh to Gordon Castle (Manley, 1969). For the London area, the observations can be standardized from 1668 onwards. To do the like for eastern Scotland set a much greater problem; stations are further apart, relief and consequent orographic effects are much greater and more varied. One cannot for example link the old Aberdeen Observatory record with Dyce, Craibstone or Mannofield.

From the experience gained when Miss Shaw and I set out to assemble data from journals kept in the London area it became evident that, in regard to snow, the majority of the 'amateurs' before the days of officially organized observations produced results comparable with the 'C' and 'D' climatological stations today. To quote: George Smith, who had retired from his post as Queen Anne's Proctor, kept his journal at Richmond from 1713 to 1745. Over the years 1729–45 he produced an annual average of 8·7 days with sleet or snow; this is about the same as the Wisley average today. For the same period Dr James Jurin, who was not only an active physician but also Secretary of the Royal Society, produced an average of 12·5; it seems reasonable to treat these as 'D' and 'C' respectively. Jurin's average is further supported by Hooker in north Kent and at Tonbridge. Later, between 1786 and 1807, Hoy at Sion House averaged 13·8, Bent at Paternoster Row 18·4. Howard's average beginning in 1797 was about the same as Hoy's during the period of overlap, and distinctly below that of Belville at Greenwich, who began in 1811. Hence for purposes of reduction to a common standard it is reasonable to regard Bent and Belville as 'B', and Hoy, Jurin and Howard as 'C', while Smith, as 'D', produces results comparable with those of the Royal Horticultural Society's later Chiswick record, also 'D', which began in 1826 (regard being paid to the effects of intermittent severe seasons). Between London and Yorkshire, 18th-century averages can also be compared with the results from the long and apparently very consistent daily observations (1748–63, 1777–89) kept by Thomas Barker at Lyndon in Rutland, which are to be reasonably regarded as 'C'.

The interesting point is that few of these early journals give, for snow-days, averages so low as to lead one to rank them much below 'D', just as they are rare today. Cary's record kept in the Strand (1786 onwards) gives such low figures as to lead to the suspicion that his observers merely noted the weather at the time when they read the instruments; the like applies to Cowe's journal (1797–1838) at Sunbury-on-Thames; in Scotland, the early Edinburgh journal (1731–36) has already been mentioned.

Among the Scottish stations the early record from the farm of Mains of Mause, at about 600 feet 4 miles north of Blairgowrie, is also regarded as a definitely low 'D'. There is only a very brief overlap with either Belmont Castle (on inspection, probably 'C', and generally comparable with the near-by Kettins agricultural station in this century), or with the much more distant Sheffield, which again, when compared with Barker's Lyndon averages, must be ranked as 'D'. Within a few miles there is also the daily MS. record of weather (non-instrumental) entered by James, Duke of Atholl from November 1755 to December 1763. This I have very recently inspected among the Atholl MSS. through the courtesy of the Aberdeen University Library and the Atholl Estates Office. Most of it refers to Dunkeld House, only 10 miles distant, and the Duke's frequency of days with sleet or snow is consistently about 1·5 times that at Mause. Detailed comparison of daily entries confirms that the observer at the farm paid little attention to events in the night, or to the slight passing showers characteristic of eastern Scotland, or to days when rain probably predominated over sleet. A single year's observations (1762) by Skene at Aberdeen this judgement of the Mause journal as far as snow is concerned. The overall support average of 22 days in a period not characterized by a predominance of mild winters certainly looks low (Crieff, at 478 feet, averaged 27, Kettins and Perth 21, between 1914 and 1938; incidentally, over the period 1922–38 Leuchars also averaged 22).

This is not to say that past averages, especially in the late 18th century, should be the equal, or nearly so, of today's; the evidence does suggest that decadal averages are likely to range between about 0·8 and 1·4 times those of our present experience, i.e. the last 30–40 years.

Much of Mossman's long Edinburgh series likewise depends on 'climatological observations' lying from 'D' to 'C', if not indeed even lower for occasional periods, as we have seen. In order to continue his series after 1896 we can use the climatological record kept at the Blackford Hill Observatory, whose purpose is primarily astronomical. Like the older Glasgow University Observatory, Blackford Hill, as we have seen, gives comparatively low figures (average 21) but they are to all appearance very consistent and the product of a well-established daily routine until 1967, after which there are some gaps. It can also be noted that from 1887 onwards to 1896 Mossman's figures were those of his own station and that they too were lower than the annual totals for 'Edinburgh' as reported in '*Observations at stations of the Second Order*'. There is also an overlap with the old Leith observations (1876–1920) for which the *Book of Normals* quoted an average of 17, much below those then given for Aberdeen (34), Dundee (25), or Shields (23); it would therefore be reasonable to treat Leith as 'D', despite the fact that, with Aberdeen and Shields, it was a telegraphic station adjacent to the North Sea.

The list of older records and their classification for purposes of standardization is given below. In several instances it is also necessary to consider what adjustment should be made for altitude. This is not always easy in eastern Scotland as one must try to distinguish the effects of sharply rising coasts in Aberdeenshire, or hills such as the Lammermuirs and the Pentlands, in triggering off the instability showers so characteristic of winter and spring, from the effect of altitude alone. High totals since 1960 at Dyce (242 ft) are noteworthy.

Good climatological stations close to the east coast give averages between 20 and 30 south of Aberdeen and north of the Tees. Inland at 280–360 m (900–1200 ft) where we have Balmoral, Braemar, Dalwhinnie, Glenmore Lodge, Achnagoichan, Braes of Glenlivet, Tillypronie, and Kindrogan for example, averages around 60 are more general and this would suggest a rate of increase of between 3 and 4 days/100 ft in the eastern Highlands; the lack of first-class airfields at higher altitudes, however, makes it difficult to say how much larger the rate of increase would become for 'A' stations.

What is clear is that the rate of increase of the annual average frequency of 'snow-days' with altitude is considerably more rapid in Scotland than in south-east England; this of course might fairly be expected having regard to the greater frequency of small amounts of precipitation in the form of light passing showers accompanying the prevailingly greater lapse rate in the lower layers of the atmosphere. In broad terms the rate of increase for the North Pennines–Borders is about twice that in southern England (cf. Bellingham, Leadhills) and approaches three times as great in the Highlands. Lamb's two-way relationship between occurrence of snow and the thickness pattern (Lamb, 1953) can also be recalled, together with the northward decline in the average height of the freezing level (Murray, 1950).

It is noteworthy that in the central Highlands the numbers of days with snow by 'C' or 'good climatological observation' becomes about equal to the number of days with snow-cover at around 300–360 m (1000–1200 ft). But at still higher altitudes persistence of snow-cover is largely a function of the departure of temperature below the average together with frequency of snowfall. With the aid of the observations of the Snow Survey and other upland records it has been demonstrated how much more rapid is the increase with altitude in persistence of snow-cover on the mountains of northern Scotland, compared with the south (Manley, WMO Norwich Meeting, 1975).

Representative yearly totals since 1708 are given in the columnar diagram (Figure 1) as ratios, to single decimals, of the average for 1941–75, regarded as unity. This average had been calculated from the annual totals at 10–12 stations between Dishforth in North Yorkshire and Craibstone, centred on the Forth–Tay region; apart from the airfields, stations have been chosen with to all appearance consistent records whose category can be fairly judged and allowed for; effort has also been made to allow for altitude. The annual totals at a number of the most useful stations are tabulated, from which it will be evident that even today there must frequently be an element of judgement in the weighting of the figures. This applies increasingly with regard to all the observations before about 1900. Before 1771 we are largely dependent on distant stations and on single series with little corroboration. These early years should therefore be treated with additional caution until, perhaps, more observations come to light.

This paper would become too long if an attempt were made to standardize the figures for the individual months. It might perhaps be done roughly by noting for each month the percentage of each year's total of 'snow-days'. Those who wish to pursue the events of individual seasons should go to the original sources, taking account of the quality of the observations, the prevailing winds and the departure of the temperature above or below normal. Persistence of cold unsettled weather in spring (March–May) is likely to be the main factor leading to prolongation of the mountain snow-cover, even into July at the highest levels; for example, in 1885 on Ben Nevis. To discuss extremes of occurrence should likewise be the subject of a separate paper; at the lowland stations, occasional mention of snow in late September or early June suggests that for eastern Scotland these are limits of long standing. The report of snow lying down to 1700 ft, with sleet at 800 ft on Speyside as early as 10 September in 1976 has not often been surpassed. There remains much room for discussion of the probable amplitude of fluctuations in western Scotland, especially towards the sea. Unfortunately there is a lack of continuity and of adequate observational material; practically all stations are coastal. Even in the Glasgow area the very evident difference, taking account of temperature, between the standards of observation maintained at the old Glasgow University Observatory (1868–1921) as reported in Becker's *Geophysical Memoirs* of 1925, and those of later stations such as Paisley, Springburn Park and Renfrew–Abbotsinch make for difficulties in assessment, although these again can be reasonably resolved on the assumption that the older climatological station falls into the 'D' group in regard to snow. In Ayrshire, over 30 years, Prestwick averages 23 and Auchincruive 16; this shows the characteristic difference between an active airfield ('A') and a near-by active agricultural research station with evident interest in weather (very good 'C' or low 'B').

While there are those who may question the utility of assemblage of such data, dependent as it must be on the exercise of judgement with regard to the manner

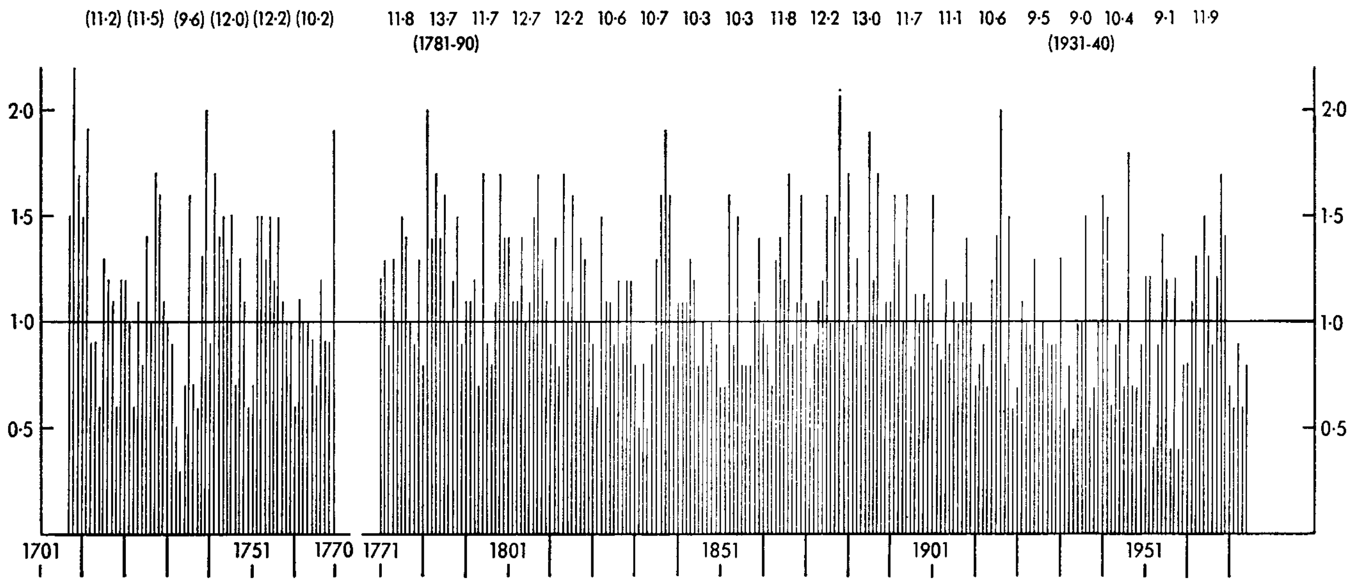

FIGURE 1—ANNUAL FREQUENCY OF SNOW-DAYS IN EAST–CENTRAL SCOTLAND, 1708–1975

Totals are shown for each decade; values before 1771 are less reliable than subsequent ones; 1·0 = average for 1941–75.

in which eye observations have been kept, the opportunities, and the criteria in vogue among earlier observers, this paper will serve to extend, reinforce and improve on Mossman's much-used Edinburgh compilation. It may also serve to draw attention to the immense mass of older meteorological journals and material awaiting critical examination by those interested in climatic fluctuation in these latitudes. Fluctuations in the frequency of snow when averaged over decades are closely associated with fluctuations in the temperature of the winter months (November to April) and can be used to assist in the reduction of earlier temperature records, whose dependence on imperfect instruments, exposures and techniques leads one to seek such other means of corroboration as may be found. Scotsmen eager to investigate the meteorological conditions prevailing on particular days since the earlier 18th century may also find the list of sources convenient.

I have to express my thanks to the Shell Organization for a personal research grant in aid of work on past records; to the Marquess of Bute for the privilege of examining manuscripts in his private library, and the help of his archivist Miss Armet, to the Librarians in charge of manuscripts in the National Library of Scotland, and quite recently, to the Atholl Estates Office; to the university libraries at Aberdeen, Glasgow, St Andrews and Durham; to the City Library at Sheffield, also to those of Perth, Inverness and Keighley; to the Meteorological Office Edinburgh with its collection of older Scottish journals; to the Scottish National Record Office, and to the County Record Office at Kendal. Lastly, it remains a pleasure to acknowledge much help from Miss Elizabeth Shaw in earlier work on Scottish snow.

I am indebted to the officers of the Royal Society, the Bodleian Library, and the British Museum for the opportunity to consult MSS.

References

ASHMORE, S. E. 1952 Records of snowfall in Britain. *Q J R Met Soc*, **78**, pp. 629–632.

BUCHAN, A. 1880 The meteorology of Gordon Castle, Banffshire, 57° 38′ N. LAT., 3° 4′ W. LONG., from July 1781 to November 1827, from observations made by James Hoy, F.L.S. *J Scot Met Soc*, **5**, pp. 59–83.

LAMB, H. H. 1955 Two-way relationship between the snow or ice limit and the 1,000-500 mb thicknesses in the overlying atmosphere. *Q J R Met Soc*, **81**, pp. 172–189.

MANLEY, G. 1940 Snowfall in the British Isles. *Met Mag*, **75**, pp. 41–48.

1958 On the frequency of snowfall in metropolitan England. *Q J R Met Soc*, **84**, pp. 70–72.

1969 Snowfall in Britain over the last 300 years. *Weather*, **24**, pp. 428–437.

MOSSMAN, R. C. 1896 The meteorology of Edinburgh, Part I. *Trans R Soc Edin*, **38**, pp. 681–756.

1897a The meteorology of Edinburgh, Part II. *Trans R Soc Edin*, **39**, pp. 63–207.

1897b The non-instrumental meteorology of London, 1713–1896. *Q J R Met Soc*, **23**, pp. 287–298.

MURRAY, R. 1950 Freezing level over the British Isles. *Weather*, **5**, pp. 284–287.

TABLE I—NUMBER OF DAYS WITH SNOW AT SELECTED STATIONS IN EAST–CENTRAL SCOTLAND AND NORTHERN ENGLAND

	ENGLAND, NE					SCOTLAND					ENGLAND	
	Dews	Halifax Sheffield	Alnwick	Year	Yorks Sheff	Perthshire Mause	Meigle	Edin (Moss)	Fov Aber	Moray G.C.	Lanark Cambg	Kendal
				1751	10							
				1752	23							
				1753	23							
				1754	25	23						
				1755	32	22+						
				1756		21						
				1757		27						
1708	22			1758		20						
1709	33			1759		13						
1710	26			1760		16						
1711	22			1761		10						
1712	29			1762		21						
1713	13			1763		18						
1714	13			1764		18						
1715	9			1765		17						
1716	20			1766		12						
1717	18			1767		22						
1718	16			1768		17						
1719	10			1769		16						
1720	18			1770		35						
1721	22			1771		23	(24)	20	29			
1722	15			1772		40	(25)	34	27			
1723	9			1773		21	(11)	14	19			
1724	17	16		1774		29	(22)	24	28			
1725	12	12		1775			(21)	16	12			
1726	22	19		1776			(35)	26	24			
1727	15	15		1777			(29)	27	30			
1728	25			1778			(27)	10	19			
1729	24			1779			(17)	16	14			
1730	17			1780			(32)	28	17			
1731	15			1781			(11)	12	13			
1732	14			1782			48	47		58		
1733	8			1783			28	32		48		
1734	5	3		1784			52	(26)		47		
1735	11	13		1785			30	26		57	29	
1736	24	19		1786			36	32		52	24	
1737	10	17		1787			25	13		18	11	
1738	9	12		1788			34	17		32	19	
1739	20	20		1789			37	21		52	35	
1740	30	28		1790			22	13		16	13	
1741		11	21	1791			28	10		26	26	
1742		26	—	1792			30	17		42	17	
1743		19	35	1793			37	13		45	21	
1744		23	26	1794			13	10		18	12	6
1745		20	27	1795			47	35		39	25	19
1746		24	30	1796			25	8		31	10	10
1747		11		1797			22	9		34	8	8
1748		20		1798			34	13		40	17	9
1749		16		1799			(45)	33	34	43	29	21
1750		9		1800				28	25	32	14	13

TABLE I—*continued*

	SCOTLAND						ENGLAND, N		
	Edin	Aber (Town)	Perths	Kincd (Johns)	G.C. Cull	Cambg Duns	Newc Durh	Braith	Kendal
1801	35	39+			44	24			15
1802	24	27			67	21	17		16+
1803	24	25			40	26	26		11
1804	33	33	(30)	(34)	56	19	27		16
1805	14	31	25	32	38	14	22		10
1806	22	23	(27)	25	44	24	18		13
1807	29	44	(30)	42	48	27	30	59	30
1808	33	41+	(45)	53	67	30	35	61	24
1809	30	39	33	37	61	(27)	26	40	12
1810	20	41	26	25	52		18	31	
1811	20		18	24	34		16	30	
1812	32		33	35	34		30	50	
1813	15		(15)	18	29		20	26	
1814	45		38	35	43		46	53	
1815	26		22	23	34		24	35	
1816	40		46	40	63		24	53	
1817	26		25	21	48		13	31	
1818	35		34	15	49		30	46	
1819	37		27	30	22		16	41	
1820	22		14	23	47		20	40	
1821	18		17	(20)	33		7	22	
1822	13		(13)		29		12	18	
1823	33		36		36		29	53	
1824	23		(18)		35		18	38	
1825	24		(15)		39		18	34	
1826	19		13		37		18	26	
1827	21		24		47		35	46	
1828	20		15				22	31	
1829	21	(30)	19				35	50	
1830	26	23	23				35	43	32
1831	18	18	13				16	29	16
1832	7	5	(8)				8	14	9
1833	16	16					(17)	35	11
1834	8	5						12	1
1835	10	18						35	21
1836	21	23						52	35
1837	42	31						50	34
1838	46	52						56	30
1839	30	35						51	40
1840	15	17						32	15
1841	22	18			36			35	25
1842	25	26			19			37	22
1843	19	46			44			43	18+
1844	28	37			50			41	29
1845	16	27			45			37	29
1846	11	29			46	14		14	12
1847	7				44	30		31	19
1848	7				27	(25)	21	33	17
1849	17				29	(27)	21	38	23
1850	12				38	(20)	16	23	(20)

					SCOTLAND						ENGLAND, N	
	Edin	Edin (B.H. etc)	Aber (Obsy)	Moray (Cull)	Crieff Braem	Dundee	Duns March	Shields	Sund	Durh	Braith	Kendal
1851	4			16			22			18	19	(10)
1852	6			31			15			13	15	(10)
1853	23			53			43			38+	48	42
1854	13			46			21			(18)	21	17
1855	33			58			44			(40)	49	42
1856	3			39			29			15	18	14
1857	11			29			24		(20)	16	(18+)	21
1858	14			36					15+	15		17
1859	17			58					24	18		18
1860	23			53					48	30		44
1861	18			33					23	19		24
1862	16			29					24	12		14
1863	8			26					15	(15)		12
1864	21			34					33	(34)		18+
1865	21			45	40				42	(23)		28
1866	9			46	(35)				31	(20)		25
1867	31			54	29				46	(40)		37
1868	11			35	32				21	15		23
1869	15			40	26				35	21		22+
1870	32			40	37				43	38		(35)
1871	17			32	35				26	26		
1872	11			26	31				16	16		
1873	12			23	(32)			(17)	26	19		
1874	21			41	30			(22)	28	(21)		
1875	20			23				(30)	35	23		
1876	36		32	47				31+	43	44		
1877	13		32	53				24	20	28		
1878	19		42	38				45	37	31		
1879	31		58	33				62	59	55		
1880	12		39	23	38			24	18	24		
1881	25		(59)		42	38		(45)	42	(41)		
1882	14		(33)		50	26		(25)	15	(21)		
1883	27		(48)		50	33		(30)	26	(28)		
1884	13		(25)		39	31		8	17	(20)		
1885	14		30		58	23		15	23	(20)		
1886	37		60		52	55	65	33	49	64		
1887	19		38		45	25	37	28	32	54		
1888	25		50		42	44	59	38	49	64		
1889	13		37		45	19	29	21	28	37		
1890	18	26	26		27	19	25	16	29	31		
1891	17	20	31		32	25	33	23	29	35		
1892	33	36	52		48	32	30	38	52	60		
1893	17	26	38		44	30	32	26	26+	39		
1894	15	20	29		48	26	31	17	20	28		
1895	30	36	64		62	34	25	35	42	53		
1896	10	11	26		34	25	12	14	13	22		
1897		20	41		44	23	22	26	27	41		
1898		18	37		45	15	17	24	24	27		
1899		18	35		51	25	29	24	25	35		
1900		(25)	26		48	25	28	27	24	38		

TABLE I—*continued*

	SCOTLAND								ENGLAND, NE			
	Edin (B.H.)	Aber (Obsy)	Braem	Balm	Dundee	Perth	Leuch	March	Shields Tynem	Sund Ackl	Durh	Eskd
1901	(26)	54	36		33			40	38	42	41	
1902	(17)	33	38		19			19	13	17	25	
1903	11	23	43		9	(15)		(21)	21	26	28	
1904	29	22	43		32	22		36	22	26	31	
1905	13	23	33	30	20	(14)		27	15	21	30	
1906	19	44		55	28	11		25	32	34	40	
1907	22	32		43	21	13		27	21	20	24	
1908	19	33		46	21	(21)		35	17	25	29	
1909	29	46		42	22	22		37	34	36	39	
1910	25	30		40	13	19		28	20	22	34	32
1911	14	19		30	9	6		22	9	14	18	40
1912	20	30	36	39	10	9		18	18	17	17	42
1913	24	19	49	39	17	23		21	16	(17)	23	35
1914	24	15	57	26	4	10		12	3		14	26
1915	28	38	77	46	12	23		27	12		35	49
1916	34	38	57	59	33	27		39	12		36	55
1917	46	68	67	94	36	41		39	31		54	75
1918	18	27	33	50	14	13		20	11		16	41
1919	44	48	79	94	29	27		28	19		(36)	92
1920	9	20	36	35	14	8		8	7		14	17
1921	14	26	40	34	16	15		14	6		9	32
1922	23	49	59	53	(15)	19	31	30	24		29	48
1923	18	42	51	37	10	21	18	23	19		22	46
1924	11	34	32	36	13	17	24	23	21		16	32
1925	23	45	51	48	20	31	31	32	28		25	54
1926	10	29	50	25	10	24	17	14	17		25	39
1927	15	40	35	27	14	37	23	21	22		20	47
1928	15	39	47	39	9	24	21	22	18		17	45
1929	9	42	41	28	10	26	22	19	23		21	46
1930	11	37	41	33	14	21	18	22	18		24	76
1931	21	48	50	34	32	25	34	23	29		24	73
1932	6	30	33	29	11	8	21	10	11		17	57
1933	17	29	27	26	11	8	18	18	21		21	43
1934	12	20	28	29	9	11	10	10	8		10	44
1935	24	32	50	41	20	22	13	17	23		20	53
1936	20	34	45	46	12	22	17	29	18		17	52
1937	36	57	49	54	26	26	36	30	34		37	71
1938	15	20	23	23	16	15	12	11	12		12	40
1939	12	23	38	25	14	13	13	16	12		15	39
1940	18	39	43	29	24	18	25	19	27		22	43
1941	35	50	69	54	35	34	41	33	33		29	57
1942	32	53	56	31	33	32	32	21	27		(43)	54
1943	10	24	45	16	9	13	10	11	11		13	31
1944	20	42	66	33	20	20	20	12	14		17	55
1945	20	37	38	20	28	18	20	21	20	21	21	42
1946	16	30	47	17	16	11	14	11	12	13	13	40
1947	38	59	73	37	33	39	48	(17)	37	54	44	70
1948	13		40	28	14	27	17	(16)	8	13	8	41
1949	13	15*	51	29	14	17	23		10	14	12	43
1950	17	26*	56	—	11	24	22		19	26	26	43

*Turnhouse

	SCOTLAND									ENGLAND, NE			SCOTLAND	
	Edin B.H.	Edin Turnh	Edin E.Craig	Aber Manno	Braem Balm	Dundee	Perth	Leuch	March	Tynem	Ackl	Durham (Hough-all)	Eskd	Dyce
1951	26	38		32	88	25	26	30		23	32	37	73	
1952	24	34		24	65	23	23	33		30	47	40	56	
1953	9	11		(15)	36	10	11	10		14	14	13	23	
1954	20	22		24	56	23	22	28		22	26	20	44	
1955	40	39		(50)	76	39	28	46		35	46	37	58	
1956	24	35		40	67	24	25	36		29	44	36	51	
1957	9	20		13	37	6	9	8		10	8	10	32	
1958	23	39		41		33	22	39		34	37	34	49	
1959	6	13		19		14	9	10	10	12	10	10	27	
1960	10	23	16	26		19	14	23	22	20	26	23	34	
1961	16	25	19	31	36	20	20	23	21	28	27	18	42	45
1962	21	32	31	36	61	26	20	29	36	33	39	30	69	55
1963	31	43	29	(37)	52	29	23	40	42	46	48	33	58	57
1964	12	26	13	18	41	10	13	21	13	18	27	12	50	22
1965	28	46	27	(46)	86	40	27	46	43	45	52	27	71	75
1966	21	44	23	40	66	28	32	44	32	31	48	18	88	64
1967	16	31	13	(25)	55	18	12	28	21	22	33	20	64	57
1968	—	44	27	26	53	25	23	45	36	43	47	23	69	66
1969	—	57	29	44	75	35	35	56	43	57	61	36	81	69
1970	(21)	48	26	37	61	26	31	51	40	52	55		83	66
1971	—	22	10	15	34	14	12	21	10	17	24	16	47	32
1972	—	21	16	10	33	7	11	27	9	9	19	11	53	18
1973	20	31	18	35	58	19	7	29	21	17	23	19	57	57
1974	19	20	13	14	37	13		20	21	9	18	12	57	27
1975	28	23	12	34	40	13		27	27	19	32	21	51	43

APPENDIX

LIST OF SOURCES AND CLASSIFICATION FOR PURPOSES OF STANDARDIZATION

SCOTLAND

Edinburgh: 1731–36, 1771–1896. Mossman's compilation from several journals. *Trans R Soc Edin*, **38** and **39** (1896 and 1897). largely C

Perthshire: Mause (Blairgowrie) 600 ft. 1754–74. MS., author uncertain, at Perth Burgh Library. See also Coates, *Perths Nat Hist Soc*, 1916. D

Dunkeld (for most part) non-instrumental. M.S journal of James, Duke of Atholl. Nov. 1755–Dec. 1763. C

Meigle (Coupar Angus) 200 ft, Belmont Castle, 1771–99. MS., (James Stewart-Mackenzie, Lord Privy Seal for Scotland). Private Library, Marquess of Bute. Very well kept. C

Pitlochry (500 ft). 1804–25, and near Perth 1826–32. MS., (James Ramsey). Meteorological Office Library, Edinburgh. D

Crieff (about 350 ft). 1865–74. MS. Meteorological Office Library, Edinburgh. C

Aberdeenshire: Foveran (coastal). 1771–81. MS., (G. Watson of Fiddes). Aberdeen University Library. D

Aberdeen (about 80 ft ?). 1799–1810. MS., (Prof. Scott). Aberdeen University Library. C

Aberdeen (town). 1829–41. MS., (G. Innes). Meteorological Office, Edinburgh. D

Alford (350 ft ?). 1843–46. MS. notes. Meteorological Office, Edinburgh. C/D

Moray region: Gordon Castle. 1781–1827. In Buchan's paper, *J Scot Met Soc*, **5**, 1880. generally B

Culloden. 1841–80. Buchan, *J Scot Met Soc*, **7**, 1882, p. 178. C

Lanarkshire:	Cambuslang. 1785–1809. MS., (Revd Dr James Meek). Glasgow University Library.	C
	Glasgow (University Observatory). 1886–1921. L. Becker, *Geophys Mem, Met Off,* No. 23, 1925.	D
Kincardineshire:	1804–21. MS., author and location uncertain, believed to have been near Johnshaven. Meteorological Office, Edinburgh.	C+
Berwickshire:	Duns. 1846–57. MS. interrupted, some estimates needed. Meteorological Office, Edinburgh.	D

NORTHERN ENGLAND

Yorkshire:	Near Dewsbury (250 ft). 1708–40. MS., (W. Elmsall). Archives, Sheffield City Library. Some years doubtful.	mainly D
	Halifax (350 ft). 1724–27. MS. letters (Nettleton). Royal Society Library.	D
	Sheffield (300 ft). 1734–55. MS., (Dr T. Short). Bodleian Library.	D
	Braithwaite (750 ft). 1807–57. MS., (A. Shackleton). Keighley Borough Library.	C+
Westmorland:	Kendal (150 ft). 1794–1809. MS., (Jonathan Dalton). Manchester Lit Phil Soc.	D
	Kendal (200 ft). 1830–70. MS., (W. Fisher). Meteorological Office Library, Bracknell.	C
Northumberland and Durham:	Alnwick (200 ft ?). 1739–46. MS., (D. Hastings), interrupted. British Museum.	D
	Newcastle (150 ft). 1802–33. MS., (J. Losh). Newcastle Lit Phil Soc.	C
	Durham (340 ft). 1848–1950. University Observatory MS. before 1884. Gaps before 1870 filled by estimation from Wylam (1854–71). Newcastle Lit Phil Soc.	largely C, some B
	Sunderland. 1857–1913. *Pub West Hendon Observatory,* **4** (Backhouse).	C+

All later observations abstracted as totals from Meteorological Office publications or the *Journal of the Scottish Meteorological Society.*

Classifications:

Aberdeen University (1876–1947)	B
Mannofield (1951–75)	C
Dundee (1881–1975)	C
Leith (1876–1920)	D
Perth (1903–73)	C
Braemar–Balmoral (since 1880)	mostly C
Marchmont (1886–1948)	C–
Edinburgh (Blackford Hill) 1896–1967. Routine, but very consistent.	on whole D
Glasgow Observatory (1886–1921)	D
Leuchars (1922 onwards) becoming A about 1954	C
Eskdalemuir (1910–75)	A
Dyce (1961–75)	A
Pitreavie (1961–75)	B
Acklington (1945–75)	A
Shields (1876–1923), Tynemouth (1924–75) with Seaham (1873–75)	varying C–B–C–B
Durham (1848–1950) continued by near-by Houghall (1951–69) and Hartburn Grange (1971–75) some B, and early D before 1866. B from 1881 to 1915.	generally C

Equations used for standardization: $A = 1{\cdot}1B + 4 = 1{\cdot}3C + 6 = 1{\cdot}5D + 8$.
Adjustment, approximate, for altitude above 100 ft: add 1·5(D) to 3(A) per 100 ft, for eastern Scotland.
References to relevant papers have been given in the text and bibliography.

551.511.32

BAROCLINIC INSTABILITY IN A REVERSED SHEAR FLOW

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SUMMARY

The term 'reversed shear flow' is defined and some properties of a baroclinic wave developing in such a flow are described. A numerical model is used to investigate the structure of a polar air depression which was observed to develop under reversed shear flow conditions.

1. INTRODUCTION

The idea that developing depressions grow by converting potential energy which is available in the mid-latitude baroclinic zone to kinetic energy was first proposed by Margules (1903). Many studies using numerical and analytical models have led to a more detailed understanding of the structure and growth of baroclinic waves (see for example Charney (1947), Eady (1949), Green (1960)). These investigations dealt primarily with occasions when the thermal wind and the progression of the disturbance are in the same direction as this is the usual situation. Occasionally the wind at the steering level, the level at which the wind speed and phase velocity of the wave are equal, is in the opposite direction to the thermal wind. Eady (1949) pointed out that this condition exists in the lower stratosphere and that the wave solutions are very similar to those which he obtained for the more common situation. It is desirable that the thermal wind and steering level wind be parallel, otherwise the efficiency of the baroclinic instability process is reduced, at least when the mean flow is in a steady state.

On the planetary scale in the lower troposphere, mid-latitude westerly winds almost invariably increase with height. However, on the synoptic scale the opposite situation, described here as 'reversed shear flow', occasionally exists. Reversed shear flow is defined as uniform, horizontal flow in which the mean wind at a given level is parallel but opposite in direction to the thermal wind at that level. It may also be defined in terms of a layer if the mean wind and the mean thermal wind are taken to be vertically averaged quantities.

Between Norway and Greenland it is not uncommon in winter for a northerly flow to have a southerly thermal wind, probably owing to the influence of the cold East Greenland ocean current on the western flank of the flow in contrast to the relatively warmer water of the Gulf Stream on the eastern side. In northerly flow over the north-east Atlantic in winter the time required for the lowest 300 mb of the atmosphere to attain a surface-induced temperature gradient is of the order of one day.

This paper discusses the structure of a lower tropospheric disturbance in a reversed shear flow and describes a polar air depression which exhibited the unusual features which result from development under these conditions.

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2. Necessary conditions and observed structure

Consider a wave-like perturbation embedded in a reversed shear flow. Its motion is such that relatively warm air lies to the left of its path with colder air to the right. Horizontal advection would cause the warm air to move behind the trough so that kinetic energy will be gained at the expense of available potential energy only if ascending motion predominates behind the trough with descending motion in the cold air ahead. This pattern of motion requires low-level mass convergence behind the trough, divergence ahead of the trough and the reverse situation above the level of non-divergence. The effect of the reversed shear flow is to reverse the usual configuration of vertical motion and divergence fields relative to an observer at the surface. Since cold air lies ahead of the trough at low levels the trough will slope forward with height.

If the perturbation is considered in a frame of reference moving with the wind at the steering level there is no difference between frictionless baroclinic development in a reversed shear flow and in a flow in which the thermal wind and steering level wind are in the same direction since, in that frame of reference, there is no horizontal motion of the mean flow at the steering level.

On 10 December 1976 a south-easterly thermal wind was observed, particularly below 700 mb, near the Faeroes, when the mean flow was from the north-west. The 1000–700 mb thickness and selected 850 mb geostrophic winds at 00 GMT (Figure 1) illustrate the large region in which a reversed shear flow existed. A weak trough, which was apparent on the surface analysis (Figure 2), deepened and crossed the Orkney Islands before continuing south-eastwards into the North Sea. The wavelength of this disturbance was 700 $\pm$ 150 km and it moved with a phase speed of 12 $\pm$ 2 m s^{-1}. Unfortunately the distribution of radiosonde observations in this region is such that the disturbance cannot be resolved at upper levels, either temporally or spatially.

The satellite picture shown in Plate I was taken from NOAA 5 at 0951 GMT on 10 December 1976 using the VHRR infra-red channel. The vortex to the east of Scotland, enlarged four times in Plate II, coincides with the observed

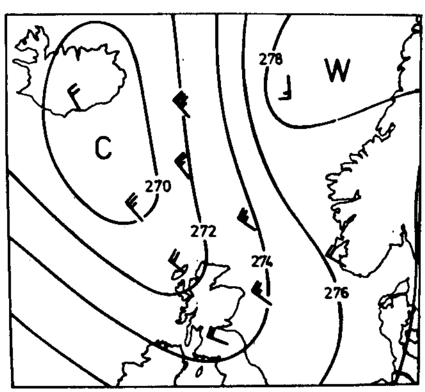

FIGURE 1—THE 1000–700 mb THICKNESS AND SELECTED VALUES OF THE 850 mb GEOSTROPHIC WIND AT 00 GMT ON 10 DECEMBER 1976

Thickness contours are in decametres.

surface trough and indicates large-scale ascent behind the centre of the wave with less-organized, shallower, cumulus convection ahead of the trough. A second vortex lying between Scotland and Iceland is interesting because it does not display this structure. However, no synoptic analysis of this disturbance has been possible since no surface or upper-air observations were made in this area. Furthermore, observations from stations in the Faeroes and the north of Scotland in the subsequent 24 hours showed no evidence of this feature.

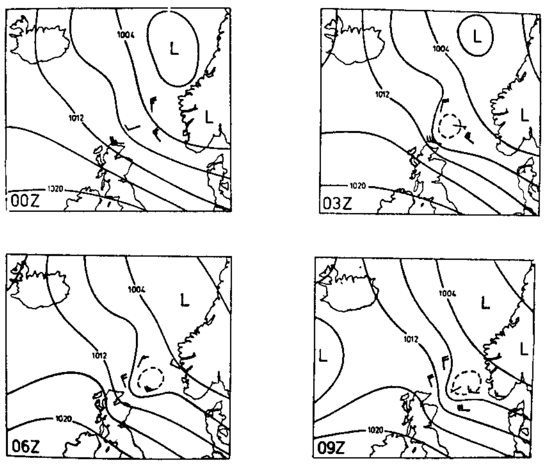

FIGURE 2—SURFACE PRESSURE ANALYSES AND OBSERVED WINDS FROM SELECTED STATIONS ON 10 DECEMBER 1976

3. NUMERICAL STUDY

Normal mode solutions were obtained in a linear, quasi-geostrophic model for growing disturbances which resemble the observed depression in phase speed, growth rate and wavelength when the mean flow parameters correspond to those observed at 00 GMT on 10 December 1976. The model has previously been used to simulate polar low development (Duncan, 1977) and was originally described by Brown (1969). A detailed description of the model will not be given, but it is necessary to state the assumptions which are inherent in its derivation. Horizontal variations in wind speed and static stability are ignored in the mean flow, which is confined to a channel of width 1200 km with horizontal lids at 1000 and 400 mb. The quasi-geostrophic vorticity and omega equations, in linear form, are solved on a two-dimensional grid across the channel. Advection of the earth's vorticity is neglected, as are friction and surface heating and the meridional variation of the Coriolis parameter (β effect). A small, random perturbation at the initial time eventually grows into the most unstable normal mode which would develop under the predetermined conditions of wind and static stability. Solutions are considered to be obtained when the real and imaginary parts of the wave speed are found to vary between grid points by less than 0·05 m s^{-1}.

These assumptions are somewhat restrictive, but the model solutions are intended only as a first approximation to the observed disturbance. The finite channel width is chosen to correspond approximately to the transverse wavelength but the value chosen obviously affects the wavelength of the most unstable wave. Similarly the inclusion of surface heating and friction is important in modelling the development of polar lows although their neglect does not invalidate the use of simple quasi-geostrophic baroclinic waves as a first approximation. A reversed shear flow will usually, although not necessarily, have a greater vertical wind shear in the boundary layer than the more normal flow. This implies an enhancement of the surface fluxes of momentum, heat and moisture. Mansfield (1974), in a study of polar lows, showed that friction and surface heating tend to shift the wavelength of the most unstable baroclinic wave in opposite senses, that both have a damping effect on growth, and that the phase speed of the wave is reduced. In a reversed shear flow the phase speed would increase as a result of the frictional lowering of the steering level.

The mean flow parameters which were employed are given in Table I. Geostrophic and thermal winds were obtained between Stornoway (58°13′N, 06°19′W) and Ørlandet (63°42′N, 09°36′E). By considering radiosonde ascents made at Stornoway, Lerwick (60°08′N, 01°11′W) and Thorshavn (62°01′N, 06°46′W) an estimate was made of the mean static stability profile over the region in which development occurred. Figure 3 shows the vertical temperature structure at these three stations and the temperatures implied by the static stabilities in Table I if a surface temperature of 1°C is assumed.

TABLE I—NUMERICAL MODEL PARAMETERS

$f = 1{\cdot}26 \times 10^{-4}\ s^{-1}$
$\beta = 0\ s^{-1}\ m^{-1}$
Channel width = 1200 km
Horizontal grid length = 100 km
Vertical grid length = 50 mb

Pressure *mb*	Static stability *$m^2\ s^{-2}\ mb^{-2}$*	Mean flow velocity *$m\ s^{-1}$*
400 ($\omega = 0$)		
		3·5
500	0·0191	
		5·0
600	0·0175	
		7·5
700	0·0172	
		10·0
800	0·0064	
		12·0
900	0·0047	
		13·5
1000 ($\omega = 0$)		

The most unstable wave identified in the numerical model has a wavelength of 900 km and a phase speed of 10·8 m s^{-1} (Figure 4). It is therefore suggested that the observed disturbance was baroclinic in nature and that its structure was probably similar to that of the 900 km wave in the numerical model. The amplitude and phase of the streamfunction, vertical velocity and thermal perturbations of this wave (Figures 5 and 6) vary with height in a manner which is consistent with the idealized reversed shear flow baroclinic wave described in the previous section. It is particularly interesting that the thermal and streamfunction perturbations are almost in phase except near the steering level.

The rate of conversion of eddy available potential energy to eddy kinetic energy, C(Ae,Ke), and the redistribution of eddy kinetic energy brought about

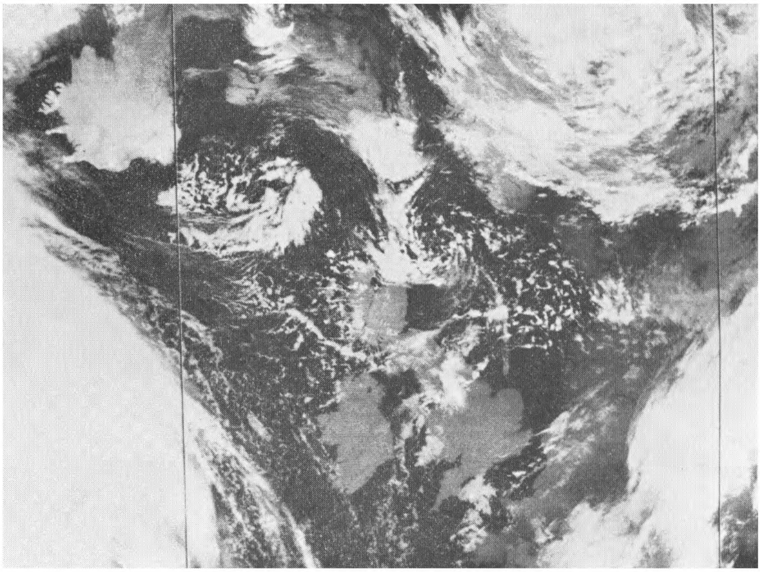

PLATE I—SATELLITE PICTURE FROM NOAA 5 TAKEN AT 0951 GMT ON 10 DECEMBER 1976 IN THE VHRR INFRA-RED CHANNEL

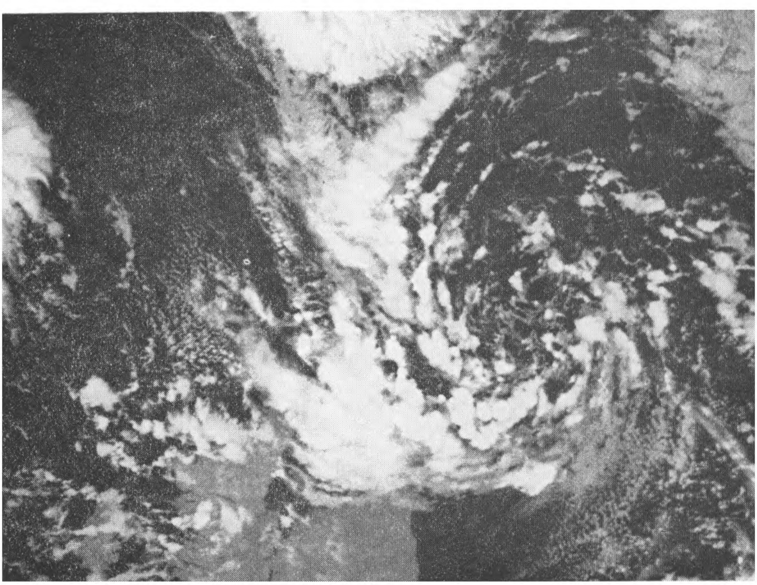

PLATE II— ENLARGEMENT (×4) OF THE VORTEX TO THE EAST OF SCOTLAND IN PLATE I

Photographs by the Department of Electronics and Electrical Engineering, Dundee University

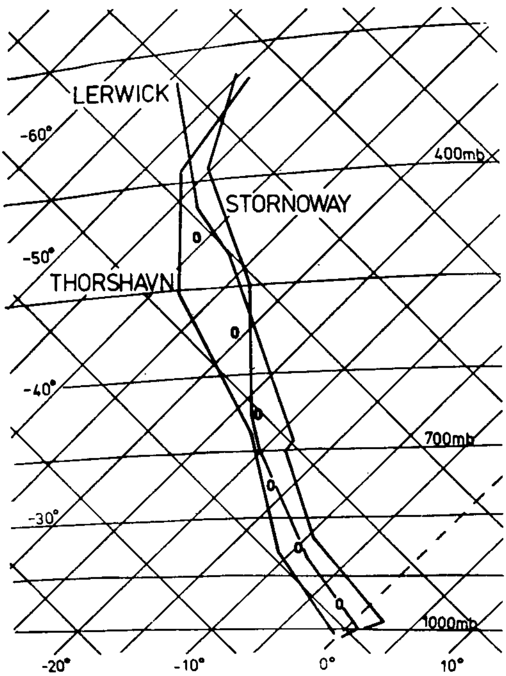

FIGURE 3—TEMPERATURE SOUNDINGS AT LERWICK, STORNOWAY AND THORSHAVN AT 00 GMT ON 10 DECEMBER 1976

Open circles indicate the temperature profile implied by the static stabilities in Table I if a surface temperature of 1°C is assumed.

by the action of pressure forces, not shown, are very similar to those found in previous studies of polar lows (Duncan, 1977). The eddy kinetic energy production due to C(Ae,Ke) is largest at 800 mb and the vertical redistribution of eddy kinetic energy is such that the maximum kinetic energy of the perturbation is found at the surface.

4. DISCUSSION

The development of a low-level trough in a reversed shear flow has been described. In spite of the scarcity of upper-air information the structure of the vertical motion field of this disturbance, illustrated by a satellite photograph, appears to conform to that postulated by consideration of the properties of a reversed shear flow.

It has also been shown that in a simple linear, quasi-geostrophic model the most unstable baroclinic waves which develop under conditions similar to those which existed on 10 December 1976, resemble the observed perturbation in wavelength, phase speed and growth rate. Although friction and surface heating were neglected in obtaining this first approximation it appears that their inclusion would not be inconsistent with the results obtained. When the thermal wind and steering level wind are parallel baroclinic development is possible. Since reversed shear flows are unlikely to extend through great depth in the troposphere the disturbances will be of short wavelength and will be more likely to develop over water surfaces where frictional damping is less.

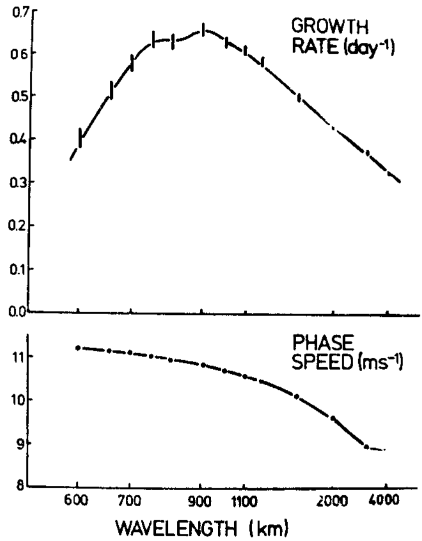

FIGURE 4—GROWTH RATE AND PHASE SPEED AS A FUNCTION OF WAVELENGTH FOR NORMAL MODE SOLUTIONS OBTAINED BY USING THE MODEL PARAMETERS SHOWN IN TABLE I

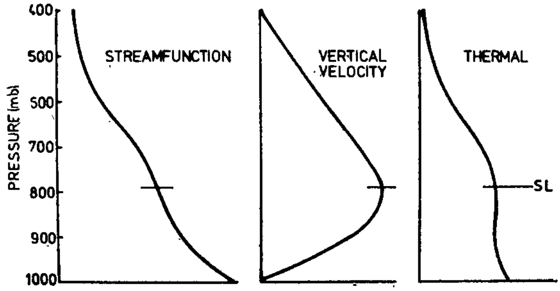

FIGURE 5—VERTICAL PROFILES OF AMPLITUDE OF THE STREAMFUNCTION, VERTICAL VELOCITY AND THERMAL PERTURBATIONS IN THE 900 km WAVE

SL indicates the steering level. The horizontal scale is arbitrary.

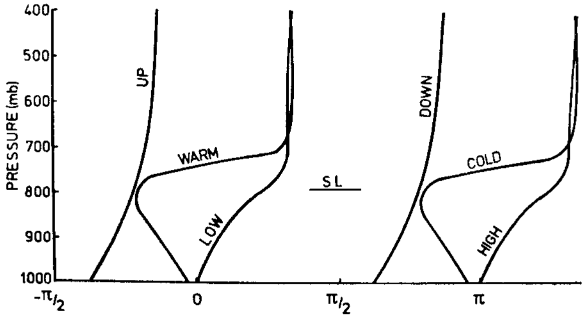

FIGURE 6—PHASE RELATIONSHIP BETWEEN STREAMFUNCTION, VERTICAL VELOCITY AND THERMAL PERTURBATIONS IN THE 900 km WAVE

SL indicates the steering level.

REFERENCES

BROWN, J. A.	1969	A numerical investigation of hydrodynamic instability and energy conversions in the quasi-geostrophic atmosphere. *J Atmos Sci*, **26**, pp. 352–375.
CHARNEY, J. G.	1947	The dynamics of long waves in a baroclinic westerly current. *J Met*, **4**, pp. 135–162.
DUNCAN, C. N.	1977	A numerical investigation of polar lows. *Q J R Met Soc*, **103**, pp. 255–267.
EADY, E. T.	1949	Long waves and cyclone waves. *Tellus*, **1**, pp. 33–52.
GREEN, J. S. A.	1960	A problem in baroclinic instability. *Q J R Met Soc*, **86**, pp. 237–251.
MANSFIELD, D. A.	1974	Polar lows; the development of baroclinic disturbances in cold air outbreaks. *Q J R Met Soc*, **100**, pp. 541–554.
MARGULES, M.	1903	Über die Energie der Stürme. *Jahrb Zentralanstalt Met, Wien*, pp. 1–26.

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THE MK 3 CLOUD BASE RECORDER—A REPORT ON SOME OF THE POTENTIAL ACCURACY LIMITATIONS OF THIS INSTRUMENT

By H. A. DOUGLAS* and D. OFFILER
(Meteorological Office, Bracknell)

SUMMARY

For the last nine years nodding-beam cloud-base recorders have been in operational use as an aid to observers, and there are currently some 80 such instruments in service in the UK Meteorological Office. No official document on the expected limitations on the accuracy of this instrument was ever issued but several users have suspected that it systematically underestimates the height of the cloud base. A theoretical error analysis supports such a hypothesis and gives an indication of the possible magnitude of such an error. Evidence from two field trials is presented which qualitatively agrees with the theoretical analysis but shows that the theoretical interpretation does not yet account for all the apparent differences obtained in practice. A new balloon-borne device for identifying cloud base, with which it is hoped to establish the limits of uncertainty, is described.

* Now at Meteorological Office, RAF Strike Command, High Wycombe.

1. Introduction

In 1968 the current design of the UK Meteorological Office Cloud Base Recorder (Mk 3 CBR) was introduced into operational service as an aid to observers at airfield sites. The main advantage of the Mk 3 CBR (described briefly in section 2) over the cloud searchlight was that it could operate in daylight. As with any new instrument, a full test program was carried out before its introduction. The instrument was designed so that any bias in the system would tend to give a low height indication, thus erring on the side of safety. At the time of the introduction of the Mk 3 CBR its limitations and design principles were explained to the user, but no document gave details or an indication of the possible errors.

In 1973 a theoretical study was undertaken (Painting and Williams, unpublished internal report) of these effects and some of the conclusions are presented in section 3. A study (National Weather Service, 1971*) was also undertaken in the United States of America with similar results. Independently of these studies, observers and others working with the instrument in the field began to suspect a systematic difference between its readings and other estimates of the height of the cloud base, and initiated their own investigations. The results of two such investigations are presented in section 4, and the evidence supports the conclusion of the theoretical approach.

As part of an evaluation and development program intended to lead to proposals for a replacement for the Mk 3 CBR, a Cloud Height Remote Indicating System (CHRIS) has been developed to help establish the limits of uncertainty inherent in the Mk 3 CBR. The operating principles of CHRIS are briefly introduced in section 5.

2. The Mk 3 CBR—theory of operation

The Mk 3 CBR uses the simple laws of trigonometry as applied to right-angled triangles. A transmitter unit, by opto-mechanical means, produces a 1 kHz pulsed beam of light which scans through a vertical sector of the sky. The rate of the scan is controlled by a drive-cam shaped so that the rate of change of height of the beam above the receiver is nearly constant over its full range. The receiver unit, at a fixed known distance (350 ft) from the transmitter, accepts scattered light from vertically above itself, and a phase-sensitive detector is used to identify any return from the transmitter unit. At all times the position of the pen arm on the recorder unit is related to the angle of the transmitter beam by means of a magslip† transducer. When the receiver identifies a return, the chart is marked appropriately. One scan (i.e. one upsweep and one downsweep) over the height range 100–4000 ft takes about one minute.

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* Washington, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service. Evaluation of Common Ceilometer Technology. *NOAA Tech Mem NWS T & EL* 13, 1971.

† A magslip is a commercially produced device for relaying angular motions in a precise way.

3. Theoretical consideration of possible error sources

(a) *General*

When considering the design of the Mk 3 CBR, possible sources of error were identified as belonging to one or more of the following features:

(i) The 2° beamwidth of the transmitted beam and the 2° acceptance angle of the receiver.
(ii) The magslip alignment.
(iii) The optical alignment.
(iv) The function cam.
(v) The receiver electronics.
(vi) The base line accuracy.

Each of these features will be considered in turn, and in each case the 'error' will be related to the 'indicated height' (i.e. the height as actually recorded by the Mk 3 CBR).

(b) *Beamwidth error*

The principle of this error is illustrated by Figure 1. The receiver unit's cone of acceptance is the triangle ARB, whilst the transmitted beam is given by triangle ATZ and the cloud base is assumed to be horizontal. The point Y is the intersection of the centre lines of the transmitted beam and the angle of acceptance of the receiver. The receiver responds to light scattered by the cloud, and thus in the limiting case (as illustrated by Figure 1(a)), the receiver identifies cloud when the leading (on the upsweep) or trailing (on the downsweep) edge is at A. In this case, whilst the true height is 'h_1', the instrument only indicates a height of 'h' (see Table I). Figure 1(b) illustrates the ideal case, in which the sensitivity is such that the receiver 'sees' cloud at the precise instant at which point Y is coincident with the cloud base—and in this case there is no error. This is also the position of maximum return signal, and thus if the instrument indicates a cloud base at a height of 'h', the true height must lie between 'h_1' and 'h'. As it is important not to miss an indication of cloud, and as the cloud may have varying droplet density distributions each implying a different scattering function, the sensitivity, which remains constant throughout the scan cycle, is set between the limits illustrated by Figures 1(a) and 1(b). As it is difficult to estimate the 'typical' setting accurately, a value mid-way between 'h' and 'h_1' (see Table I) has been taken to represent the uncertainty due to beamwidth and the acceptance angle of the receiver.

Table I—Estimation of the errors due to beamwidth

Height as indicated by CBR *ft*	Maximum true height while within tolerance *ft*	Maximum difference (indicated minus true) *ft*	Expected difference (half maximum) *ft*
100	107	−7	−4
250	263	−13	−7
500	533	−33	−17
1000	1117	−117	−59
1500	1771	−271	−136
2000	2505	−505	−253
3000	4288	−1288	−644
4000	6663	−2663	−1332

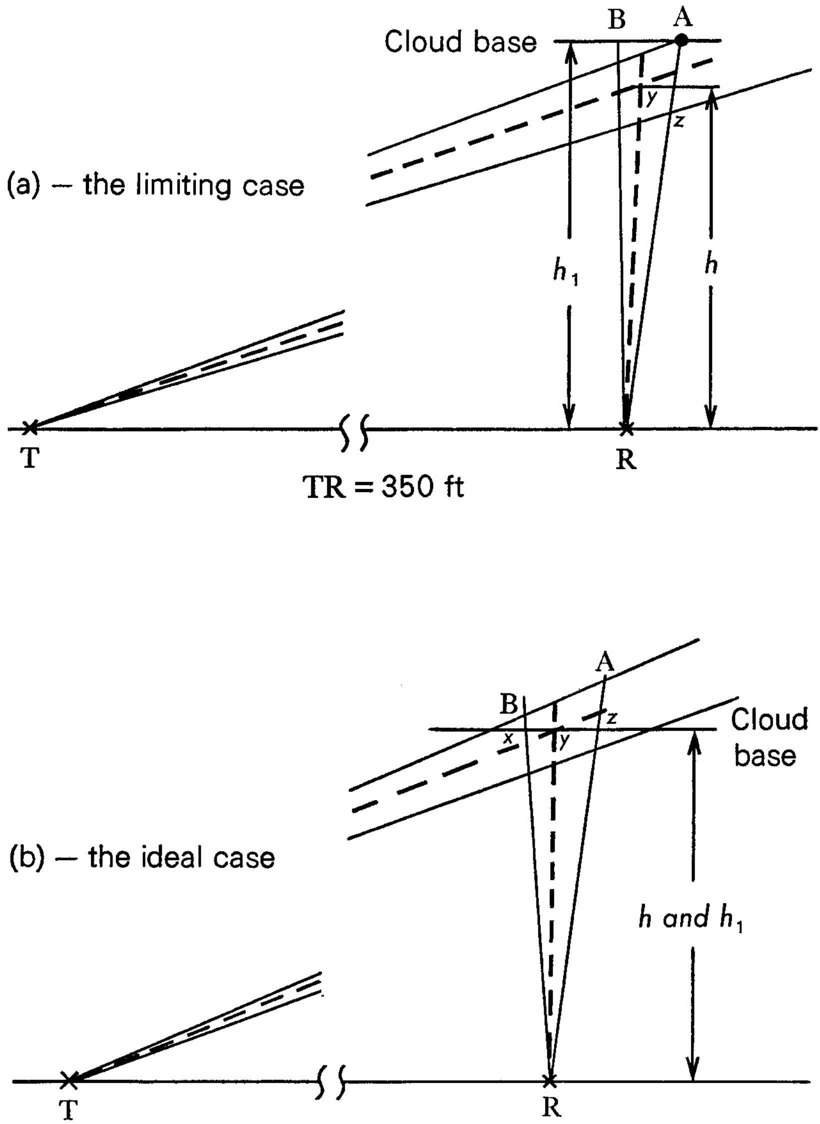

FIGURE 1—DIAGRAM SHOWING THE RELATIVE GEOMETRIES OF THE TRANSMITTED BEAM AND THE CONE OF ACCEPTANCE OF THE RECEIVER OF THE UNITED KINGDOM MK 3 CLOUD BASE RECORDER

In (a), the limiting case, the errors due to beam spread are at a maximum.
In (b), the ideal case, there is no error due to beam spread.
– – – centre of transmitted beam and cone of acceptance
—— limits of transmitted beam and cone of acceptance
h_1 true height of cloud base
h indicated height of cloud base

In this as with all these estimates, the instrument is assumed to be operating within the normal tolerances laid down for installation and routine maintenance.

(c) *Optical alignment*

The main optical components can be set to a high degree of precision and thus the most critical feature is the accuracy with which the lamp filament can be positioned, since small errors in this setting have the effect of an angular beam misalignment. An error of 1 mm is possible; this is equivalent to an angular error of 0·5°, and the result of such an error is indicated in Table II.

TABLE II—ESTIMATION OF THE ERRORS ASSOCIATED WITH A 0·5° MISALIGNMENT OF THE ANGULAR BEAM

Indicated height (ft)	100	250	500	1000	1500	2000	3000	4000
Difference (ft)	±3	±5	±10	±29	±62	±106	±231	±402

(d) *Magslip alignment*

The best possible setting, in operation, of the two magslip units is equivalent to 0·25° and thus the errors will be half those indicated in Table II. By the nature of its design the receiver element of the magslip unit (in the recorder) will always be trying to follow that of the transmitter element (in the transmitter). The difference in their settings at any instant is a measure of the error and is related to any acceleration in the transmitter unit. The use of cams makes such additional magslip errors negligible.

(e) *Function-cam and base-line errors*

Compared with the previous errors these can be neglected, but they are listed here for completeness. The error due to the function cam would not exceed 0·25 per cent of the indicated height and thus the error at 4000 ft would be less than 10 ft. An error in the base line, say of 3 ft—an extreme case—would only give an error of 35 ft at 4000 ft and about 8 ft at 1000 ft.

(f) *Receiver electronics*

This is a difficult area in which to assess the uncertainty or error. The major source of uncertainty will be associated with the performance of the phase sensitive detector and in particular the time taken to 'recognize' a return signal. The various factors which would contribute to an overall uncertainty figure have never been systematically investigated and such an investigation has not yet been warranted. Thus no figures will be included for receiver electronics errors although, in practice, there will be such an error, perhaps of a similar magnitude to that of the optical alignment error. For comparison, Table III shows the error caused by a 250 ms delay (the maximum delay measured during trials) in 'recognizing' a return signal.

TABLE III—ESTIMATION OF THE ERROR ASSOCIATED WITH A 250 ms DELAY IN 'RECOGNIZING' A RETURN SIGNAL

Indicated height (ft)	100	250	500	1000	1500	2000	3000	4000
Difference (ft)	±5	±7	±14	±42	±89	±154	±344	±603

(g) *Implications of the theoretical study*

The errors listed above are all independent, and apart from that of 3(b), will give a zero mean error when considered over a large number of observations and installations. The beamwidth error is, of necessity, single-sided and is in practice the most likely cause of the largest error. Table IV shows the aggregate of the errors and is expressed in the form of an expected true height (for each selected indicated height) as a result of the beamwidth error, and a standard deviation σ where $\sigma = (\Sigma\sigma_r^2)^{\frac{1}{2}}$ and $\sigma_r (r = 1 \ldots n)$ is the standard deviation of each of the other errors. The σ_r are deduced on the assumption that these errors are distributed normally with extreme values of $5\sigma_r$. These results are indicated in Figure 2 which shows the beamwidth error and uncertainty bars (2σ) at the selected heights.

It should again be emphasized that the standard deviation does not include a true allowance for the receiver electronics error (only the delay error is included), and thus Figure 2 should be taken only as a rough indication of the likely error in any reading taken from a Mk 3 CBR chart.

TABLE IV—SUMMARY OF THE EXPECTED ERRORS DUE TO BEAMWIDTH, AND THE STANDARD DEVIATIONS OF OTHER ERRORS FOR SOME SELECTED INDICATED HEIGHTS

Indicated height *ft*	Expected true height *ft*	Standard deviation of the expected height (due to errors other than beamwidth) *ft*	Indicated height minus expected height *ft*
100	104	1·25	−4
250	257	1·9	−7
500	517	4	−17
1000	1059	11	−59
1500	1636	23	−136
2000	2253	39	−253
3000	3644	86	−644
4000	5332	150	−1332

4. SOME EXPERIMENTAL OBSERVATIONS

Whilst the Mk 3 CBR has been in operational use, forecasters and meteorological observers have made their own comparisons with other sources of information; at some stations, on their own initiative, they have conducted detailed comparisons between observations from other sources and the values obtained by the Mk 3 CBR. The results of two of these comparisons are presented here to illustrate the nature and magnitude of the results.

During 1975 the staff at Liverpool Airport undertook a comparison between a cloud searchlight (maximum errors due to all sources but with the instrument correctly adjusted as described in the Handbook of Meteorological Instruments, Part I are given in Table V) and a Mk 3 CBR sited some 800 ft from the searchlight. The results, for those heights having enough data, are given in Table VI, and the points are indicated in Figure 2.

TABLE V—ESTIMATION OF THE MAXIMUM ERRORS WITH A CLOUD SEARCHLIGHT, CORRECTLY ADJUSTED, AND ASSUMING A UNIFORM CLOUD BASE

Indicated height (ft)	100	250	500	1000	1500	2000	3000	4000
Maximum error (ft)	±17	±18	±22	±35	±57	±87	±175	±297

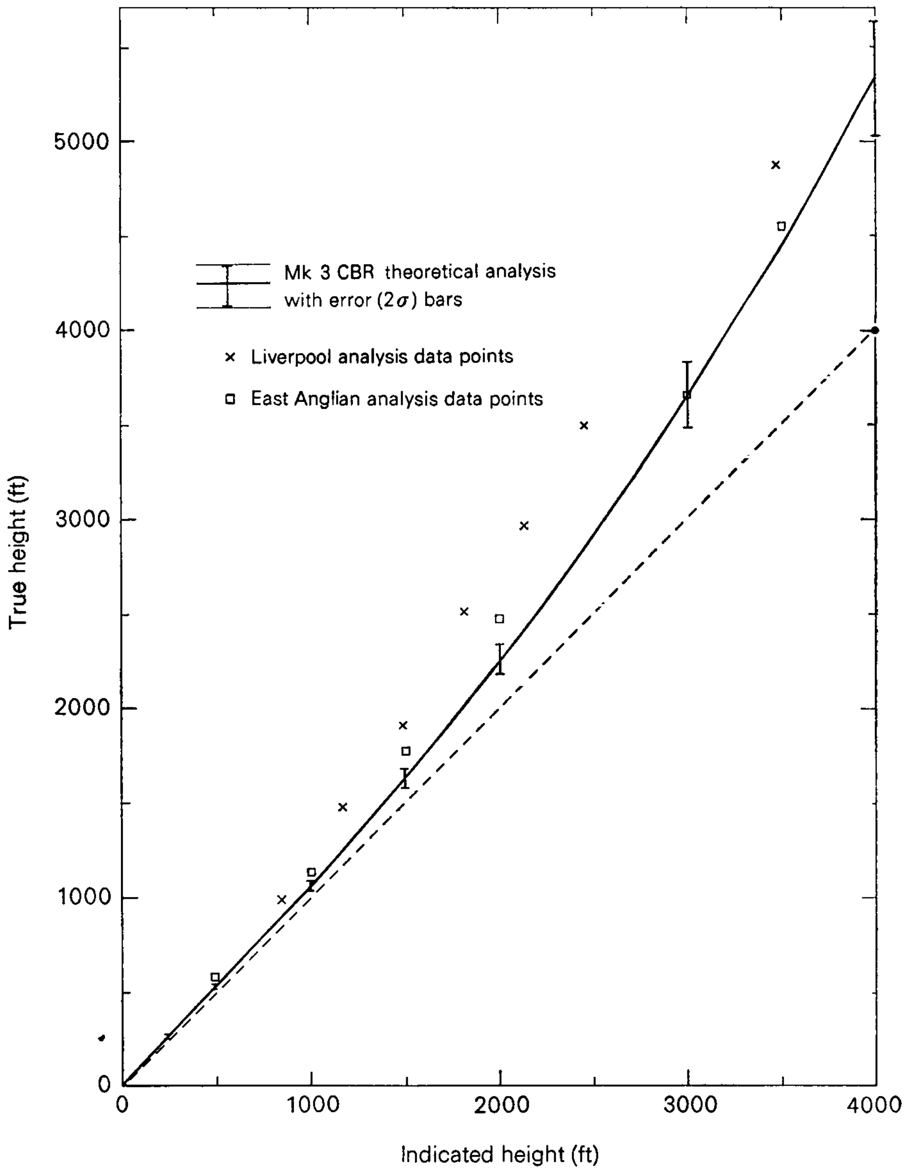

FIGURE 2—VISUAL PRESENTATION OF THE DATA IN TABLE IV SHOWING THE MAGNITUDE OF THE EFFECT OF BEAM SPREAD

The results from the two investigations at Liverpool and in East Anglia are plotted for reference. The dashed line corresponds with zero height error.

TABLE VI—SUMMARY OF THE RESULTS FROM THE LIVERPOOL AIRPORT TRIAL

Indicated height (ft)	850	1170	1490	1810	2130	2450	3465
Mean error (CBR minus searchlight) (ft)	−113	−370	−422	−694	−832	−987	−1392
No. of observations	53	30	50	36	52	24	26

The second example is from an investigation carried out at several sites in East Anglia over the period 1973–75. The comparison values were based on cloud-searchlight observations, pilot-balloon ascents and cloud heights reported by pilots. Over 500 observations were made in this study, and some of the results are given in Table VII, the corresponding points again being indicated in Figure 2.

TABLE VII—SUMMARY OF THE RESULTS FROM THE EAST ANGLIAN TRIAL

Indicated height (ft)	500	1000	1500	2000	3000	3500
Mean error (CBR minus check) (ft)	−80·5	−156	−288	−486	−650	−1053
No. of observations	36	32	60	65	31	47

Both these studies illustrate the same trend as is indicated by the theoretical study. The Liverpool comparison is systematically higher than either the East Anglian comparison or the theoretical indication. That the three studies do not agree numerically does not mean that any one study is right or wrong. Both the experimental results are higher than the theoreal and thus it could be argued that a value other than half the maximum beamwidth error should have been used. Also not all aspects of the Mk 3 CBR were taken into account and this may have some bearing on the results, and finally we do not have detailed knowledge of the performance details of the CBRs at all stages of the comparisons. Nevertheless, the three studies taken as a composite group offer strong evidence that the Mk 3 CBR systematically reads low by the level of magnitude indicated in Table IV.

5. CARDINGTON TRIAL

Part of the trials program to establish a replacement for the Mk 3 CBR will take place at the Meteorological Research Unit (Cardington) where a balloon-borne package can monitor the base of a cloud layer whilst a Mk 3 CBR operates in the vicinity. A Cloud Height Remote Indicating System (CHRIS) has been developed (Offiler, unpublished internal report), based on a series of water-content detectors spaced at 10 m intervals, and a package providing pressure and temperature (and thus height) which can be mounted on the Cardington balloon cable, the data being transmitted to a data-logging system on the ground (Figures 3 and 4).

The system was tested at Cardington, using a double theodolite system as the standard with which to measure the height of the probe, and based on these trials CHRIS was expected to measure the cloud base to within ±15 m (10 m for height error from pressure and 5 m because of the probe separation), except when the base was diffuse and therefore difficult to define to this degree of precision.

The equipment is now awaiting use during the main CBR trials program.

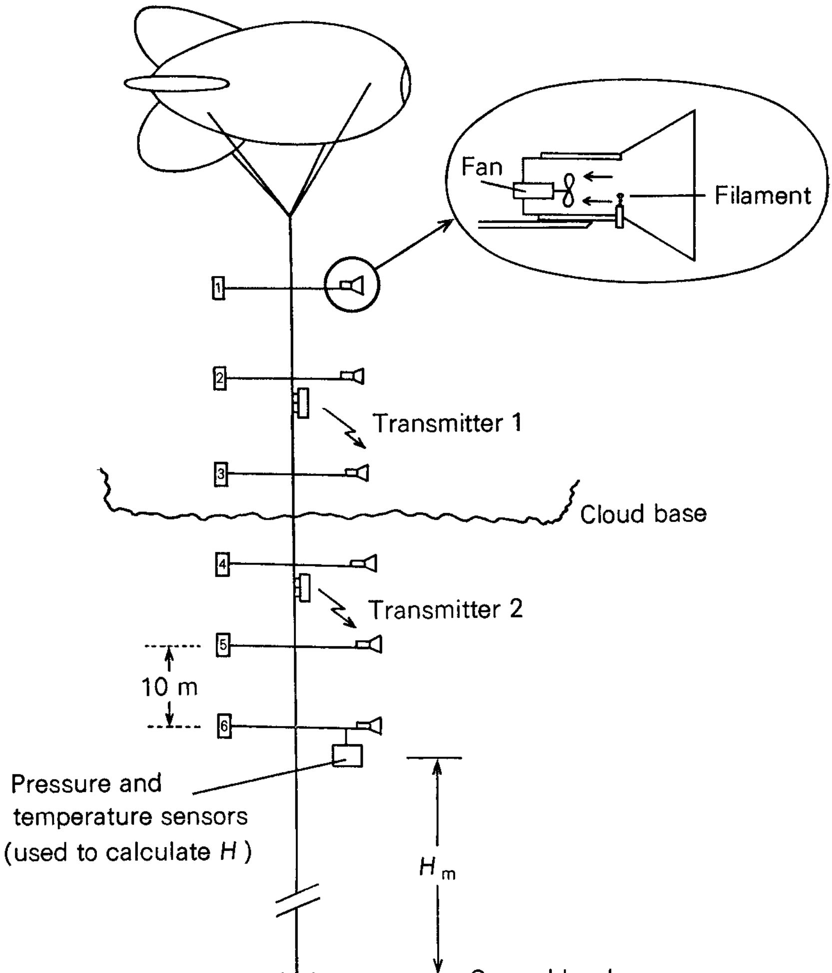

FIGURE 3—CLOUD HEIGHT REMOTE INDICATING SYSTEM (CHRIS)

A schematic view illustrating the procedure for a cloud-base mid-height amongst the array. The insert shows the probe head in schematic form.

6. CONCLUSIONS

This paper provides both theoretical and experimental evidence that the current Mk 3 CBR reads systematically low and Table IV provides an indication of the likely magnitude of the deviations. It should be noted that the errors for heights below about 1000 ft are relatively small. A problem in assessing any instrument designed to measure the height of the cloud base is the difficulty of defining

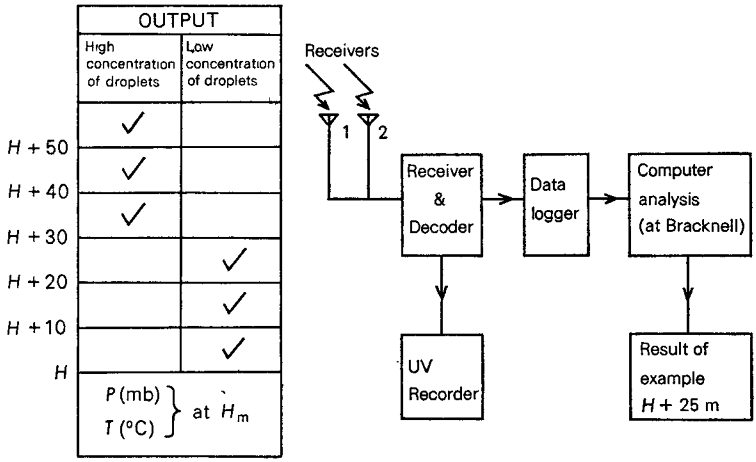

FIGURE 4—BLOCK SCHEMATIC FURTHER ILLUSTRATING THE PROCEDURE FOLLOWED IN FIGURE 3

the cloud base and a system has been developed and tested which should help to establish the relationship between the step-function in the water-content distribution near a cloud base and the height of the base as recorded by the CBR. Such information will provide an independent assessment of the height accuracy of the Mk 3 CBR.

7. ACKNOWLEDGEMENT

The authors wish to acknowledge their appreciation of the work and effort of all colleagues who have in any way provided data for this paper.

REVIEW

Climate: Present, past and future. Volume 2, Climatic history and the future, by H. H. Lamb. 235 mm × 180 mm, pp. xxx + 835, *illus.* London, Methuen; New York, Barnes & Noble, 1977. Price: £38.

When Professor Lamb tackled the writing of this authoritative book on climatic changes he undertook a monumental task. Volume 1 appeared in 1972, and Volume 2, which has now been printed, is even more impressive in its scope and the extent of its survey of the literature.

The plan which Professor Lamb adopted was a good one. Volume 1 was to contain a survey of the fundamentals of climate—the general circulation of the atmosphere and the physical mechanisms involved—together with a description of world climate as it is now. Volume 2 was to provide the climatic history and a look into the future. Separate chapters would discuss the sources of evidence on past climates, their techniques and validity, and subsequently piece together the evidence for pre-Quaternary, Quaternary, post-Glacial, Historical and the Instrumental periods. Rather unfortunately Professor Lamb must have found it difficult to adhere to his plan. Climatic change is a rambling subject in which many threads of evidence are drawn together, and Professor Lamb has been unable to resist a temptation to follow each thread, once started, far beyond the scope of the chapter as implied by its title. The result is a great deal of repetition, and a book which is longer than it need be. The task of the reader is also not made easier by a plethora of parentheses and footnotes, or by the long and involved sentence constructions.

However, the book collects together an enormous amount of information relevant to past climates. Some of it is very valuable—particularly some of the tabular matter, which runs to over 100 pages—and some of it is intriguing rather than significant—for example, the association between the average age of marrying and the mean annual temperature (p. 264).

The scientific community will undoubtedly welcome the timely publication of Professor Lamb's Volume 2 as giving a broad survey under one cover of a very diverse and scattered literature. The extensive references will be greatly appreciated and will form the starting point for many further researches. The explanations of the specialist terms and nomenclature of geologists, historians, limnologists, stratigraphers, archaeologists and others will be exceedingly welcome to meteorologists trying to understand a paper in a relevant but unfamiliar discipline. The comprehensive index will also be valued.

Much of the 'proxy' evidence of past climates is of doubtful validity. Professor Lamb weaves his way through the mass of material, rarely challenging the interpretation placed on it by the original authors. Often, however, he interpolates an interpretation of his own in terms of the atmospheric circulation, 'dust veils', or solar variations. Clearly many of these ideas have not been subjected to rigorous scientific assessment—it would not have been practicable to do so—and they may ultimately prove wrong. Nevertheless one must not belittle the role of intelligent guessing in this subject, where a coherent picture of events is built by the patient collection of many clues which in themselves have little significance. Indeed, ideas on ice-ages and continental drift were first built up on scanty and speculative evidence, but subsequently received incontrovertible and quantitative confirmation from isotope ratios and palaeomagnetic measurements.

Compared with the comprehensive treatment of the past, Professor Lamb's treatment of the present and future is far less thorough. The present is dealt with in Volume 1 mainly as a background to the understanding of climatic change. The future is included in Volume 2 mainly, one feels, for the sake of completeness. Chapter 19 on 'Man-made climatic changes' gives a general survey of the subject without any quantitative discussion in depth of the mechanisms which may, or may not, be important. Chapter 20 on 'Approaches to the problem of forecasting' makes some useful points about the way in which scientists should answer questions about future climate, but one is left uncertain as to whether the author considers that any real forecasts should be given (other than probabilities based on past statistics). An appendix gives 24 different climatic forecasts from various sources and they are compared with subsequent events to date. There are some which seem to have a germ of success. How far they have been selected because of this one cannot know, but they do seem to show that informed scientists have been able to do better than the indefinite extrapolation of trends which has often been popular—upward for temperature in the first half of this century and downward since.

Professor Lamb has certainly produced a book that will be a classic in its subject.

J. S. SAWYER

NOTES AND NEWS

Association of British Climatologists—New Directory

The Association of British Climatologists, which now forms the Specialist Group in Climatology of the Royal Meteorological Society, is preparing for publication a Third Directory of British Climatologists. Although direct contact will be made with all who appeared in the Second Directory, it is hoped that as many climatologists as possible (whether included previously or not) will write to Professor S. Gregory, Department of Geography, University of Sheffield, Sheffield S10 2TN, before the end of January 1978 for further information about inclusion.

The 15th International Conference on Alpine Meteorology (ITAM-78)

The 15th International Conference on Alpine Meteorology (ITAM-78) will be held in Grindelwald (Bernese Oberland, Switzerland) from 19 to 23 September 1978. The main subjects to be dealt with will be the influence of mountains on the weather and climate, and specific meteorological and climatological phenomena observed in mountain areas.

Those wishing to give papers at this meeting should send the title and a short summary of their proposed contributions not later than 31 January 1978 to the following address, from where further information can also be obtained:

Swiss Meteorological Institute
ITAM-78
Krähbühlstrasse 58
CH-8044 Zurich
Switzerland.

The telephone number of the Swiss Meteorological Institute is
01/34 67 20
and its Telex number is
52202.

Retirement of Mr D. G. Harley

With the retirement of Mr D. G. Harley, Assistant Director (International and Planning) on 13 December 1977 the Office has lost another of the small remaining band of pre-war entrants. Those of us who have known him and worked with him over the years will miss his cheerful presence in our ranks.

David Harley graduated from Edinburgh University in 1938 with honours in physics and entered the Office in October of that year. After some initial training (no Shinfield Park in those days!) he was soon involved in forecasting on RAF stations and was posted to Gibraltar in 1940. He was commissioned as Flight Lieutenant in the RAFVR in 1942 and returned to the United Kingdom in 1943 for further service with the Royal Air Force. Mr Harley received a Mention in Dispatches in 1944.

There followed a rather special assignment when Mr Harley joined in 1946 the small unit in Lisbon which throughout most of the war discreetly served British civil aircraft flying in and out of Lisbon. He was demobilized during that time and when he left Lisbon in 1948 there began a long period of civil aviation work both at London Airport and at Prestwick in his native Scotland. Mr Harley soon established himself as a shrewd forecaster with special experience of Atlantic problems and he was appointed Senior Meteorological Officer at Prestwick in 1960.

In 1964, by which time he was working in the new Headquarters at Bracknell, Mr Harley visited the West Indies to report, in consultation with the Director of the Caribbean Meteorological Service, on the meteorological requirements of the British Windward and Leeward Islands and British Guiana.

Mr Harley joined the International and Planning Branch (Met O 17) in 1964 and on promotion to Senior Principal Scientific Officer in 1967 was appointed ADMetO(IP), the post from which he retired. During his ten years of international work he acquired a comprehensive knowledge of the ramifications of WMO and his advice was frequently sought by members of the Directorate involved in the work of the various WMO bodies. He naturally became widely known internationally and was greatly respected and liked for his integrity and understanding. Partly as a result of his Chairmanship for a time of the WMO Executive Committee Working Group on Antarctic Meteorology he visited the USA Antarctic Expedition bases in 1969 as Official British Exchange Representative.

David Harley has a bright, lively mind with wide interests and to those who know him well there seems little likelihood that he will stagnate in retirement.

We wish Mr and Mrs Harley a long and happy retirement.

G. A. CORBY

THE METEOROLOGICAL MAGAZINE

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NOTICES

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1 monthly **Annual subscription £13.14 including postage**

Dd. 497684 K15 12/77

ISBN 0 11 724795 2
ISSN 0026–1149

Met.O.915
METEOROLOGICAL OFFICE

the meteorological magazine

FEBRUARY 1978 No 1267 Vol 107
Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.915

THE METEOROLOGICAL MAGAZINE

No. 1267, February 1978, Vol. 107

551.585.3(540)

THE ONSET AND THE NORTHERN LIMIT OF THE SOUTH-WEST MONSOON OVER INDIA

By I. SUBBARAMAYYA and O. S. R. U. BHANU KUMAR
(Department of Meteorology and Oceanography, Andhra University, Waltair, India)

SUMMARY

The weather changes associated with the onset of the monsoon at about 70 stations in India have been studied with a view to developing a specific definition for the onset of the monsoon suitable for application in fixing the northern limit of the monsoon at the time of routine analysis. It is shown that the rainfall and its nature alone should be considered for such a definition. The authors have suggested that the day when the first rainfall associated with the first north-westward progressing rainstorm is received at any place should be considered as the onset day at that place. The northern limit of the monsoon is defined as the line joining all the places of latest onset of the monsoon. The advance of the monsoon is analysed by using this definition for five seasons and the charts are compared with those of the India Meteorological Department. The differences are explained and are attributed to lack of specific definition of the onset of the monsoon for its determination in routine practice.

INTRODUCTION

The onset of the south-west monsoon over India has been considered as a special meteorological phenomenon and its study will be one of the important aspects of the MONEX-79 program. The normal date of onset at any station was determined from the characteristic rise in the cumulative mean rainfall curve at that station by the India Meteorological Department. A chart of normal onset-dates for India and neighbourhood was published by the India Meteorological Department in 1943 (see Figure 1). According to this chart the monsoon sets in over the south Andaman Sea and lower Burma by about 20 May and advances north-westwards, reaching the Indian mainland by 1 June. It reaches the northernmost limit in the extreme north-west by 1 July.

Investigations have been made in order to study the onset in relation to the changes in winds and circulations in the middle and upper troposphere over India as well as over Eurasia and the Pacific by Maung Tun Yin (1949), Koteswaram (1958), Subbaramayya (1961), Lockwood (1963), Wright (1967), and de la Mothe and Wright (1969). An attempt was made by Ramadas *et alii* (1954) to forecast the date of onset of the monsoon on the west coast of India. These investigations require precise and accurate information regarding the time of onset.

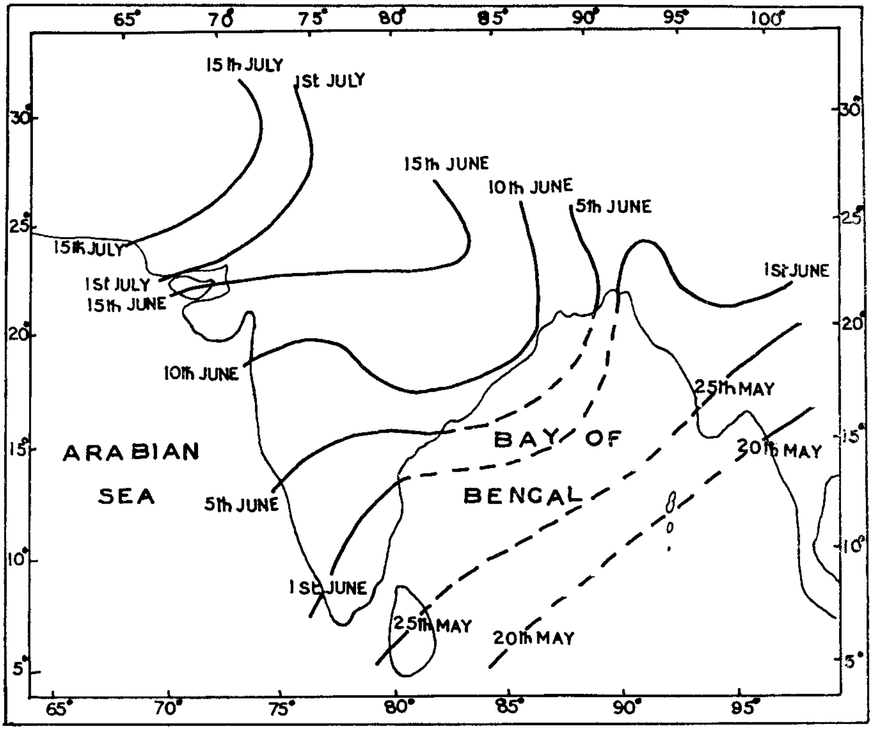

FIGURE 1—NORMAL DATES OF ONSET OF THE SOUTH-WEST MONSOON
(After India Meteorological Department (1943))

The determination of the normal date of onset of the monsoon from the cumulative mean rainfall curves is not unambiguous. This is particularly true in the areas where the pre-monsoon thunderstorm rains merge with the monsoon rainfall and in those areas where the rainfall in the monsoon season is poor. This point was brought out by Ananthakrishnan and Rajagopalachari (1964). The determination of the time of onset in individual years, which is also necessary for demarcating the northern limit of the monsoon (NLM) at the operational level, is much more ambiguous and difficult because it is not possible to have cumulative rainfall curves to the required extent for the characteristic rise to be properly noted. It became a custom to consider the changes in the other weather parameters to define the onset of the monsoon. But this was not done systematically and the precise method varied from person to person. It is necessary to have a specific definition for the onset of the monsoon so that its northern limit can be determined objectively. The need for a specific definition has also been stressed by Ananthakrishnan *et alii* (1967) who gave a criterion for defining the onset of the south-west monsoon over Kerala only, according to which 'beginning from 10 May if at least five out of the seven stations report 24-hourly rainfall 1 mm or more for two consecutive days the forecaster should declare on the second day that the monsoon has advanced over Kerala'.

WEATHER CONDITIONS IN MAY AND JULY

Since the onset of the monsoon is being considered as an event when the pre-monsoon summer conditions abruptly change to the cool, humid and rainy monsoon weather, the difference in the mean weather conditions between May and July should be due to the characteristic change in weather associated with the onset of the monsoon at any place. On this assumption, to formulate a criterion for the identification of the onset, the authors have prepared and studied the charts of 'changes' in different weather elements, where these changes are expressed as differences or ratios. Some of these charts are presented in Figures 2–6 and the salient features are discussed. For the preparation of the charts the mean values for a period of 30 years at about 70 stations published by the India Meteorological Department (1963) have been used.

The average ratios of rainfall on a 'rainy' day* in July to that on a rainy day in May (Figure 2) show that the rainfall on a rainy day increases over a major part of the country by a factor of from 1 to 2. However, in the neighbourhood of Delhi the factor is 3. In the extreme south, on the other hand, the rainfall on an average rainy day in July is less than that in May.

The distribution of numbers of rainy days in the month of May and the differences from May to July are presented in Figures 3(a) and 3(b). In the month of May the number of rainy days is less than 3 over much of the country. In a small area on the west coast near about 10°N the number of days is 10. A similar small area is present in north-east India, where the number is 15. These rains are attributed to the pre-monsoon thunderstorms. The increase in the number of rainy days is quite significant on the west coast between 13°N and 20°N. Over much of the country the number increases by more than 10.

The north-westward spread of the monsoon rains is accompanied by a fall in day maximum temperatures. In May the average maximum temperatures are a little above 40 °C except in coastal regions and in some parts of peninsular India. Figure 4 shows the extent to which the monsoon depresses average maximum temperatures. The quantity shown is average July maximum minus average May maximum. The decrease is as much as 10 °C over central India. The mean diurnal range of temperature in July as compared with May is reduced by 4–8 °C over a major part of the country. It is to be noted that these changes are not as large as those of maximum temperature; this indicates that there is a slight increase in minimum temperatures. This increase should be due to the general cloudiness of the monsoon current.

The changes in mean low-cloud amount and total cloud amount from May to July (Figures 6(a) and 6(b)) show a general increase by 2–4 oktas and 3–5 oktas respectively over the whole region except for the extreme south and north-west regions where the monsoon rains are meagre and the north-east regions where the pre-monsoon rains are frequent.

Keeping the above-described changes in view it may be assumed that the onset of the monsoon would be associated with an increase in rainfall on a rainy day by a factor of as much as 3, an increase in the frequency of rains from 1 day in 10 to 1 day in 2, a decrease in maximum temperature by 4–10 °C, a decrease in diurnal range of temperature by 3–8 °C, an increase in total

* 'rainy' days are defined as having falls of at least 2·5 mm.

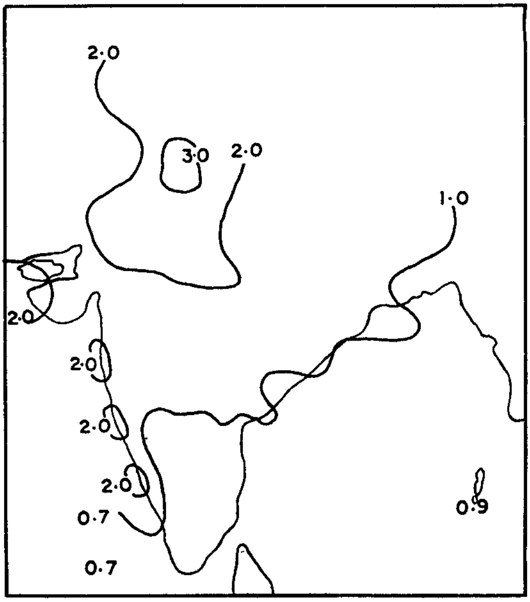

FIGURE 2—RATIO OF RAINFALL ON A RAINY DAY IN JULY TO THAT ON A RAINY DAY IN MAY

cloud amount by 3–5 oktas and in low-cloud amount by 2–4 oktas. It should also be borne in mind that there would be regional differences from these general values.

WEATHER CHANGES AND THE ONSET OF THE MONSOON IN 1975

The changes in the values of the different weather elements associated with the onset of the monsoon in 1975 have been studied in order to understand how far the May to July weather changes occur at the time of the onset of the monsoon. For this purpose the weather data published in the Indian *Daily Weather Reports* at 70 stations for a period of 15 days, one week on either side of the officially declared onset day at each station, have been critically examined.

There were rain-spells (rainfall on two or more consecutive days) at 60 stations during the periods under study. At 19 stations the declared onset day (hereinafter called 'onset day') coincided with the starting day of the rain-spell. At the rest of the stations the onset was declared 2 or 3 days after the starting of the spell. The rainfall on the onset day was 10 mm or more at 30 stations, less than 10 mm at 14 stations and nil at 14 other stations. At the rest of the stations the rainfall reports were missing on the onset day. The maximum 24 hour rainfall in the spells was 10 mm or more in 53 out of the 60 cases. The onset day coincided with the maximum-rainfall day in 14 of the 53 and 4 of the remaining 7 cases. These observations show that the declared onset day coincided neither with the first day of the spell nor with the day of maximum rainfall in most of the cases. It has been found that the average rainfall on the declared onset day was practically equal to the average rainfall on the starting day of the spells and considerably lower than the average maximum rainfall in the spells.

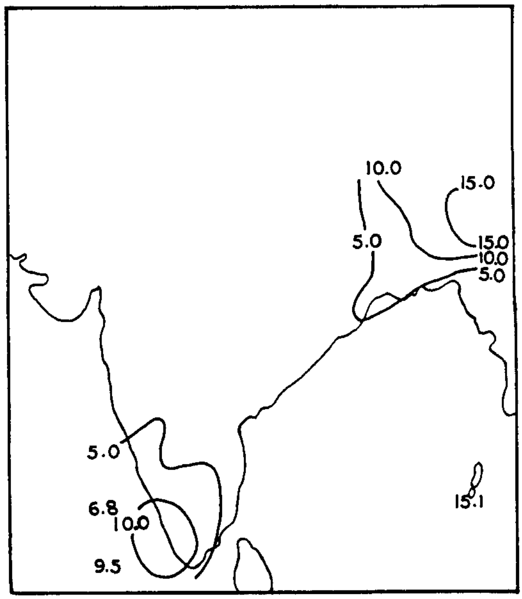

FIGURE 3(a)—NUMBER OF RAINY DAYS IN MAY

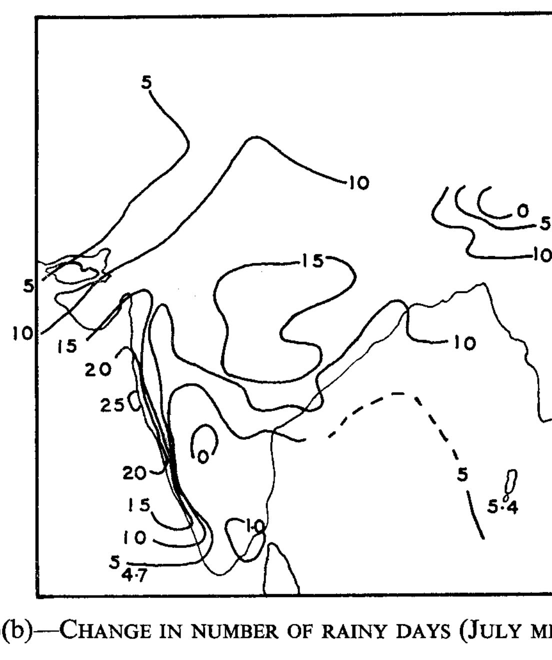

FIGURE 3(b)—CHANGE IN NUMBER OF RAINY DAYS (JULY MINUS MAY)

A drop in the maximum temperature by at least 4 °C in 24 hours during the two-week periods of study occurred at 46 stations. In 18 of these cases the change occurred on the onset day, whereas it was later in 13 and earlier in 15 cases. In general the drop in temperature followed a heavy rainfall. A

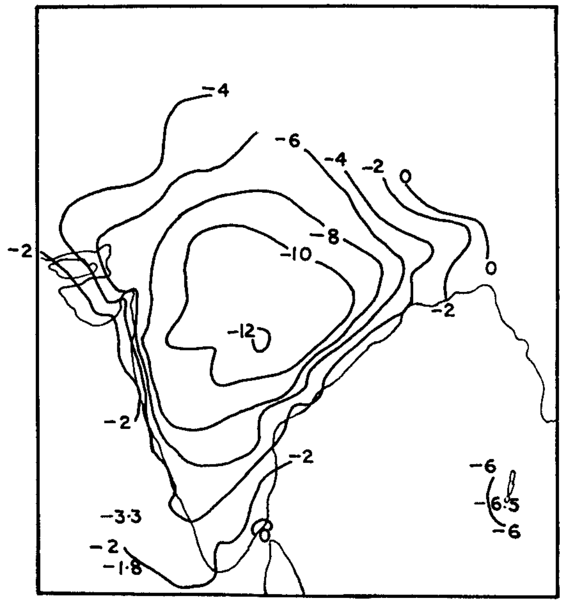

FIGURE 4—CHANGE IN MAXIMUM TEMPERATURE IN DEGREES CELSIUS (JULY MINUS MAY)

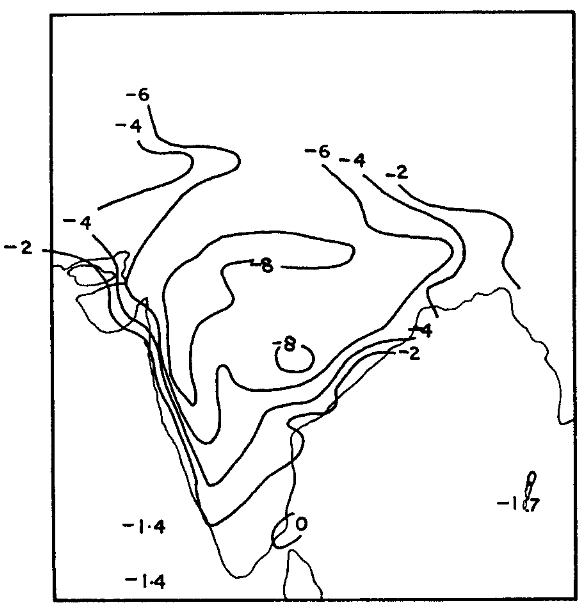

FIGURE 5—CHANGE IN DIURNAL RANGE OF TEMPERATURE IN DEGREES CELSIUS (JULY MINUS MAY)

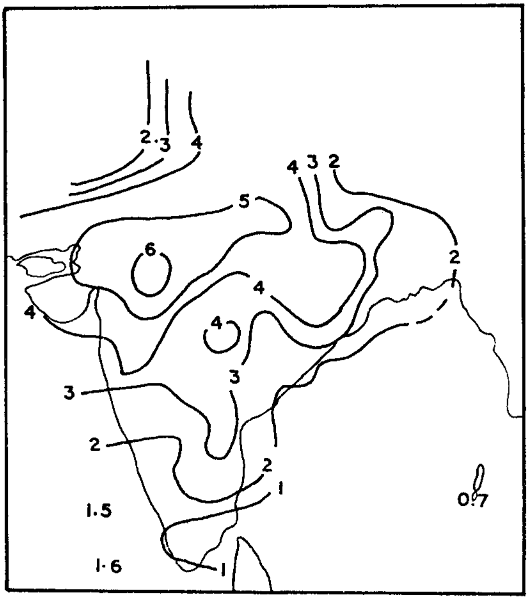

FIGURE 6(a)—CHANGE IN TOTAL CLOUD AMOUNT IN OKTAS (JULY MINUS MAY)

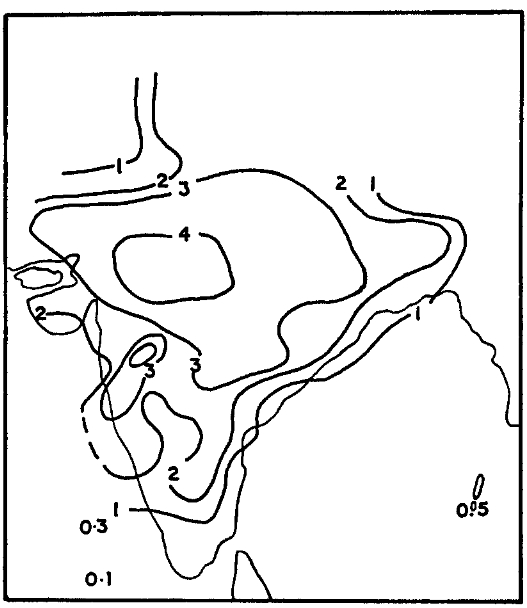

FIGURE 6(b)—CHANGE IN LOW-CLOUD AMOUNT IN OKTAS (JULY MINUS MAY) discontinuous change (4 °C drop or more in 24 hours) in the diurnal range of temperature occurred in 38 cases of which 11 were on the onset day, 8 earlier and 19 later.

An increase by at least 3 oktas in the total cloud amount and low-cloud amount occurred at 47 and 40 stations respectively. Of the former 47 cases only 5 coincided with the onset day, while 38 occurred earlier by from 2 to 4 days. Changes in low-cloud amount occurred in 12 cases on the onset day while in 20 cases the change was earlier. Thus in the majority of the cases changes in cloud amounts occurred before the onset day. Furthermore, the changes in medium- and high-cloud amounts have occurred a day earlier than changes in low-cloud amount.

The foregoing observations indicate that substantial changes in different weather parameters do occur around the time of onset, but not simultaneously. The changes are spread over 4 or 5 days in general and usually occur in the following order: (1) medium- and high-cloud amount; (2) low-cloud amount; (3) rainfall; (4) maximum temperature and diurnal range of temperature. Differences in the order do occur as well as in the time taken for the changes to take place at some stations. There were also cases where the changes took place only gradually. Hence it may not be possible to have a simple criterion involving several weather parameters and yet maintain objectivity. It is proposed, therefore, that the starting day of the first monsoon rain-spell be considered the prime factor for the determination of the onset day.

DETERMINATION OF THE ONSET AND THE NORTHERN LIMIT OF THE MONSOON

A careful study of the rains associated with the onset in several years showed that the monsoon rain-spells at individual stations were due to synoptic and subsynoptic systems which cause widespread rains. This is in contrast to some of the scattered pre-monsoon thunderstorm rains. Widespread rains due to synoptic systems do, of course, occur in the pre-monsoon season also. But the essential difference is that the synoptic systems and associated rainstorms in the pre-monsoon season move eastwards while those in the monsoon period move westwards. The onset of the monsoon at any place may therefore be associated with the first westward-moving rainstorm.

It was also found that the NLM is not a material (i.e. continuous) curve; neither is it a line of discontinuity in the pressure field or in the wind field. The NLM is a curve, south of which the monsoon has already set in. This does not mean that rains occur constantly at all places every day south of that line. The NLM can hence be obtained by joining all the places of latest onset of the monsoon or, in other words, all places which have just received for the first time rain due to the first monsoon rainstorm.

The authors have determined the NLM on every day during the period of the establishment of the monsoon over India in the years 1971–75 according to the above-stated definitions of the onset of the monsoon and NLM and have compared them with those given by the India Meteorological Department. As an example the charts for the year 1973 are presented in Figures 7(a) and 7(b). The advance of the NLM line was never uniform all along its length. The advance was confined to limited lengths on any day, depending on the size of the synoptic systems that advanced north-westwards across the NLM giving the first monsoon rains in areas where the monsoon had not previously set in.

The first official announcement of the NLM was given on 26 May (Figure 7(b)). It touches the southern tip of peninsular India and runs across the Andaman Sea and central Burma. There was a slow northward advance till 5 June. But thereafter it quickly advanced and established itself over most of the country by 14 June. Further advance took place only from 1 July and the remaining part of the country was covered by 5 July.

Figure 7(a), however, shows that, according to the present writers, the monsoon had set in over the Andaman Islands as early as 17 May. The monsoon quickly covered Burma and touched the southern tip of peninsular India by 20 May. Towards the end of the month there was a slight advance over the west coast, the north Bay of Bengal and parts of Assam. Then there was a rapid advance from 3 to 13 June while a major part of the country was covered by the monsoon. The rest of the country was covered by 5 July; this date agrees with the official date. It is to be noted that there are differences in the earlier part of the progress of the monsoon.

The delay in the official declaration of the monsoon in the Bay Islands, south peninsular India, upper Burma and north-east India was due to the rains of the first westward-moving systems having been overlooked. It is also to be noted that the official onset was, in general, some 2–3 days late according to the present writers. Similar differences were observed in the other years also. There were cases when the official dates were earlier than the dates fixed by the authors. In those cases the rains due to eastward-moving systems, or due to lows after recurvature, were considered to be monsoon rains.

In the above study the north-westward progression of the synoptic system or rain area was inferred from synoptic charts drawn at intervals of 12 or 24 hours. It should be stated here that determining the direction of propagation is sometimes quite complicated because the synoptic systems responsible for the onset and advance of the monsoon are formed, or at least affected, by troughs in the subtropical westerlies. These troughs also give rise to widespread rain areas which are sometimes contiguous with those of the eastern disturbances. One should be able to differentiate between the two rain areas. The radar and satellite surveillance of rain and cloud areas would be quite helpful in understanding the progression of the systems and hence in determining the NLM.

Conclusions

(1) Lack of specific definition of the onset of the monsoon over the Indian subcontinent, suitable for application in the routine of daily analysis, results in inaccuracy and subjectivity in the determination of the onset and positioning of the NLM.

(2) Changes in weather parameters other than rainfall, e.g. temperature and cloud amounts etc. may occur around the time of onset of the monsoon but rainfall only should be considered for the purpose of determining the onset.

(3) The onset of the monsoon may be declared on the day when the first rain of the first westward-moving synoptic system or rainstorm is received at any place.

(4) The NLM can be drawn by joining all the places of latest onset of the monsoon.

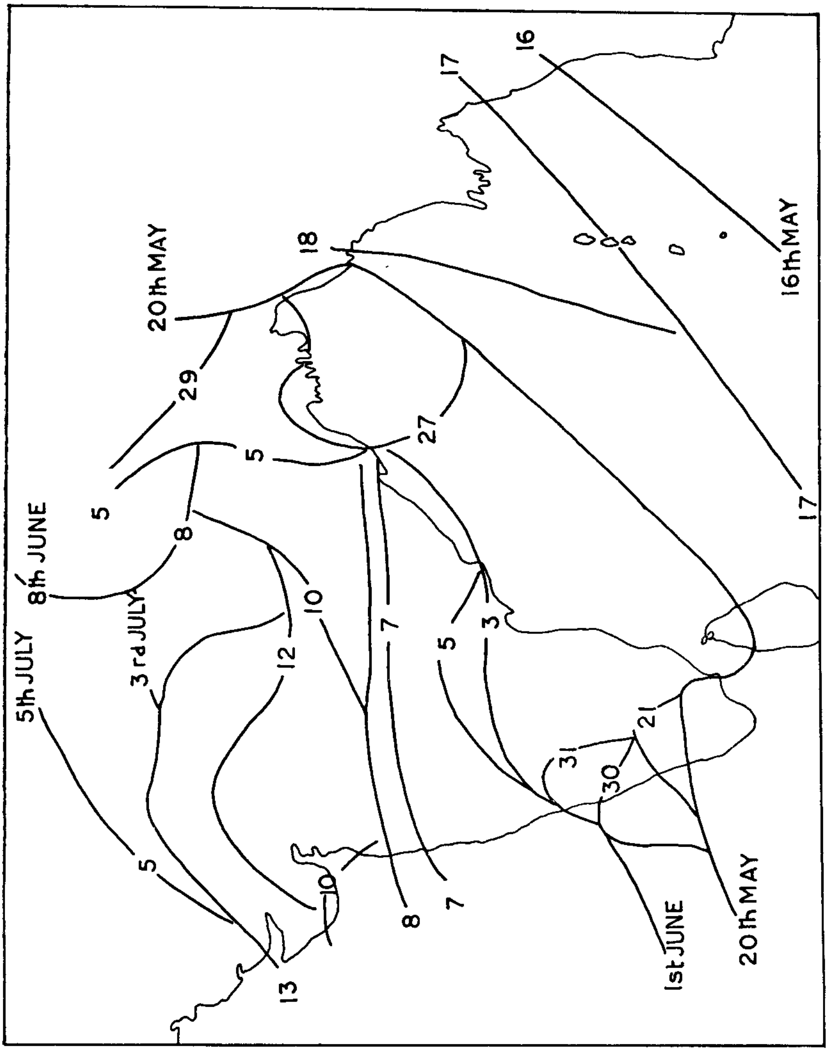

FIGURE 7(a)—PROGRESS OF THE MONSOON IN 1973 (ACCORDING TO THE AUTHORS)

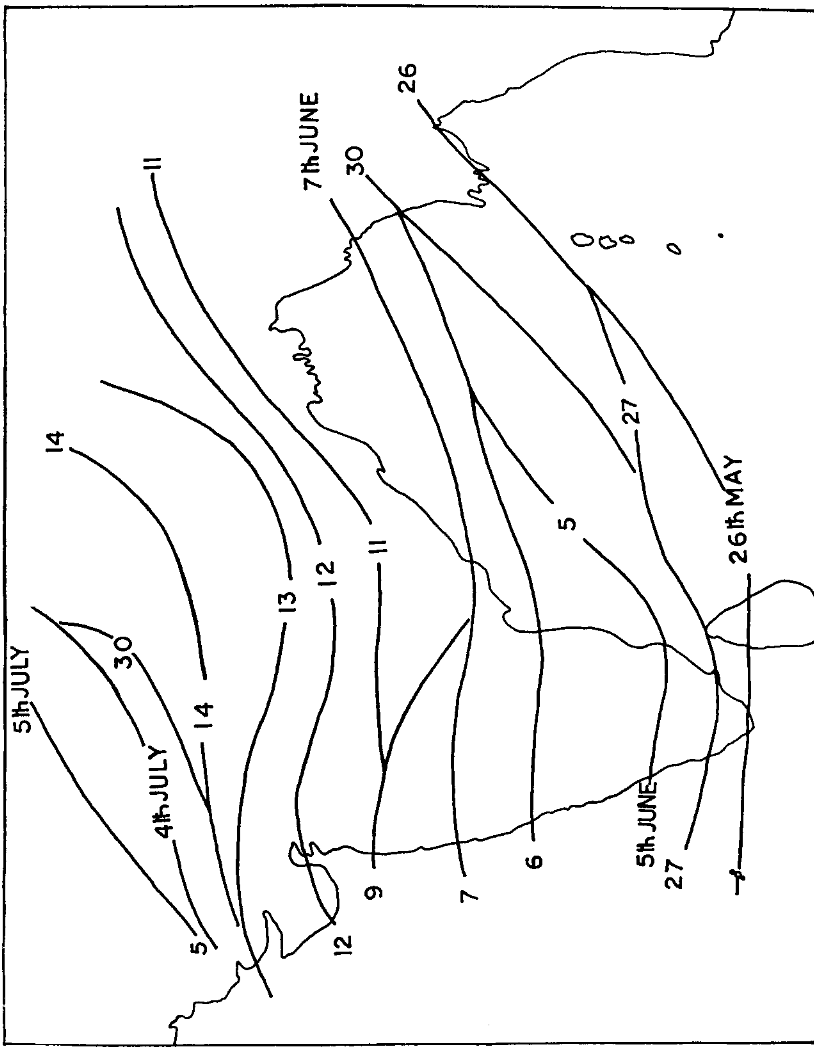

FIGURE 7(b)—PROGRESS OF THE MONSOON IN 1973 (ACCORDING TO THE INDIA METEOROLOGICAL DEPARTMENT)

(5) The NLM is neither a material (i.e. continuous) curve, nor a line of discontinuity in the pressure field or in the wind field; it does not advance uniformly all along its length, its advance normally depending on the synoptic system that is responsible for the spreading of the rain-area.

(6) Satellites and radars can play useful roles in fixing the NLM, particularly when the western and eastern disturbances are interlinked.

(7) Finally the authors wish to state that the dates of onset at a number of stations should be determined in as many individual years as possible and thence the normal dates of onset should be charted and variability figures evaluated for climatological purposes.

REFERENCES

ANANTHAKRISHNAN, R., ACHARAYA, U. R. and RAMAKRISHNAN, A. R. 1967 India Meteorological Department. Forecasting Manual, Part IV, 18: Monsoons of India, p. 9.

ANANTHAKRISHNAN, R. and RAJAGOPALACHARI, P. J. 1964 Pattern of monsoon rainfall distribution over India and neighbourhood. *Proc Symp Trop Met, Rotorua, N.Z.*, November 1963, pp. 129–200.

DE LA MOTHE, P. D. and WRIGHT, P. B. 1969 The onset of the Indian south-west monsoon and extratropical 500-mb trough and ridge patterns over Europe and Asia. *Met Mag*, **98**, pp. 145–155.

India Meteorological Department 1943 Climatological Atlas for Airmen in India.

1963 Climatological Tables of Observatories in India.

KOTESWARAM, P. 1958 The easterly jet stream in the tropics. *Tellus*, **10**, pp. 43–57.

LOCKWOOD, J. G. 1963 Winds at the 200 mb level over the tropics and sub-tropics during the seasons of monsoon change. *Met Mag*, **92**, pp. 75–84.

MAUNG TUN YIN 1945 A synoptic-aerologic study of the onset of the summer monsoon over India and Burma. *J Met*, **6**, pp. 393–400.

RAMADAS, L. A., JAGANNATHAN, P. and GOPAL RAO, S. 1954 Prediction of the date of establishment of Southwest Monsoon along the west coast of India. *Ind J Met Geophys*, **5**, pp. 305–314.

SUBBARAMAYYA, I. 1961 Studies on the Indian South-west Monsoon. Ph.D. thesis, Andhra University, Waltair.

WRIGHT, P. B. 1967 Changes in 200 mb circulation patterns related to the development of the Indian south-west monsoon. *Met Mag*, **96**, pp. 302–315.

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ON FORECASTING DRY THERMALS FOR GLIDING

By B. J. BOOTH
(Meteorological Office, RAF Lyneham)

SUMMARY

Data derived from glider flights over Salisbury Plain indicate that a minimum depth of neutral stability is required before thermals can develop. Simple discriminant analyses of small samples representing days of strong thermals and days of weak thermals show that temperatures at 1000 metres above ground level are particularly important when considering upper-air temperatures in relation to surface temperatures for discriminant purposes. If the difference between the potential temperature at 1000 metres above ground level and the maximum surface potential temperature is $\geqslant 3$ K, thermals are unlikely to be weak.

INTRODUCTION

To remain airborne, the glider is dependent on rising currents of air which develop from time to time in the free atmosphere. These may be divided into two main categories—lee waves and thermals. Although hills are normally a necessity for the formation of lee waves, thermals develop over almost any terrain subject to insolation and it is on these thermals that the pilot normally depends when making cross-country flights. When considering the possibility of a prolonged soaring flight a pilot will ask the forecaster four basic questions about the thermal prospects for the day:

(a) When will thermals start?

(b) How long will they last?

(c) How strong will they be?

(d) How high will any convection extend?

The problem of the depth of penetration has already been adequately described by Browne *et alii* (1955) and Reid and Wu (1965), but considering that soaring flights have been made in the United Kingdom since 1933 it is surprising that there is little published work to assist the forecaster in answering the remaining questions, and this despite the wealth of descriptive literature, for example Wallington (1961), that has been written.

In an attempt to shed further light on the problem a study has been made of thermals found over Salisbury Plain at various times between 1969 and 1975. A thermal for the purpose of this paper is defined as a rising current of air strong enough to enable a glider to remain airborne. At the thermal's highest point of penetration it may, or may not, be capped by cumulus, but throughout this paper 'thermal' refers to the ascending current or bubble of air beneath cumulus or blue sky. (Thermals uncapped by cumulus are called blue thermals.) Differential surface heating is probably by far the most common method of development of thermals but they can form in other ways. Close to the ground the excess temperature of warm bubbles over that of the environment is about 1 K (Murgatroyd, 1954), but at heights of above 300 m above ground level (agl) this difference is very much smaller, being about 0·2 K according to Goldney (1970) and James (1954).

Thermals are usually only strong and persistent enough from April to September to enable a glider to make a prolonged soaring flight (Wickham, 1966), so this study is restricted to data which have been gathered in these months. Although on occasion the strength of thermals in other months did reach 2 m/s, they tended in general to be weak, with vertical velocities around 1·0 to 1·5 m/s or less.

DATA

Reports of vertical velocities, *W*, found in thermals over Salisbury Plain were obtained from gliders launched by aero-tow at about 600 m above airfield level. Values of *W* are measured by the pilot's noting the rate of climb indicated on the glider's variometer. (A variometer in this context is an instrument indicating the rate of climb or descent of a glider.) Although many variometers are limited to a range of reading of ± 5 m/s (10 kn), recent modifications allow measurements of rates considerably in excess of this. In practice the simpler type of variometer is adequate for most dry thermals since it is rare for thermals to reach 5 m/s in this country.

All thermals were contacted at heights of 300 m or more agl, not because thermals have to rise to this height before developing enough to enable a glider to remain airborne, but because most of the observations were made from a Blanik two-seater trainer, and at this height the pilot would be concentrating more on landing procedures rather than on searching for thermals. All values of W referred to throughout this paper are those indicated by the variometer; no correction has been made for the rate of sink, or descent, of the glider. The rates of sink for the gliders themselves vary with the ways in which the gliders are being flown and with the types of glider. For the contemporary gliders used in this investigation the rates of sink would vary a little between 0·5 and 1·0 m/s because of differences in glider performance and by similar amounts because of the ways in which they were being flown, e.g. radius of turn, angle of bank etc. These variations are likely to have had a secondary effect on the recorded values of maximum vertical velocity (W_{max}) on different days (so far as differences in W_{max} for weak and for strong thermals are concerned) except for the addition of an approximate constant of about 1 m/s to all the values recorded.

Initially the flights were made from Compton Abbas in Dorset, 245 m above sea level (asl), but in 1973 the club concerned moved to Inkpen, 240 m asl, some 60 km to the north-east. Routine surface observations made at Upavon, 176 m asl and 20 km south-east of Inkpen, were taken to be representative of the area, whilst upper-air observations were usually obtained from Larkhill, 132 m asl (Figure 1). The Larkhill upper-air temperatures were all measured between 05 and 09 GMT but sometimes, because Larkhill soundings were not made, or because appreciable changes were taking place in the upper-air temperatures, reference was made to soundings elsewhere in England in order to estimate upper-air temperatures representative of conditions for the area (before modification by solar heating occurred).

METHOD OF ANALYSIS AND DISCUSSION

A thermal has its origins in the surface layers and may be considered as a bubble of air which breaks away from these layers under the action of various forces (Scorer, 1954; Grant, 1965). Since it is warmer than the environment at this stage of its development, and hence less dense, it will continue to rise until it reaches a zone where the density of the environment is less than that of the bubble.

In practice thermals appear to vary considerably in structure and frequency on any one day, so much so that it is not unknown for pilots based at the same airfield to encounter completely different conditions on the same day. This could be due to a number of reasons, not the least being the skill and experience of the individual pilot. In general, pilots are reasonably consistent in their condemnation of a poor day; it is on the better days that their views tend to diverge. For example, on one afternoon five consecutive flights recorded thermal strengths of 1·5, 2·0, 0·0, 2·0 and 1·5 m/s. Most pilots are satisfied if values of W consistently reach 2–3 m/s and will quite happily report that the day has been a good one for soaring. But some days are even better, with W reaching maxima of 4–5 m/s.

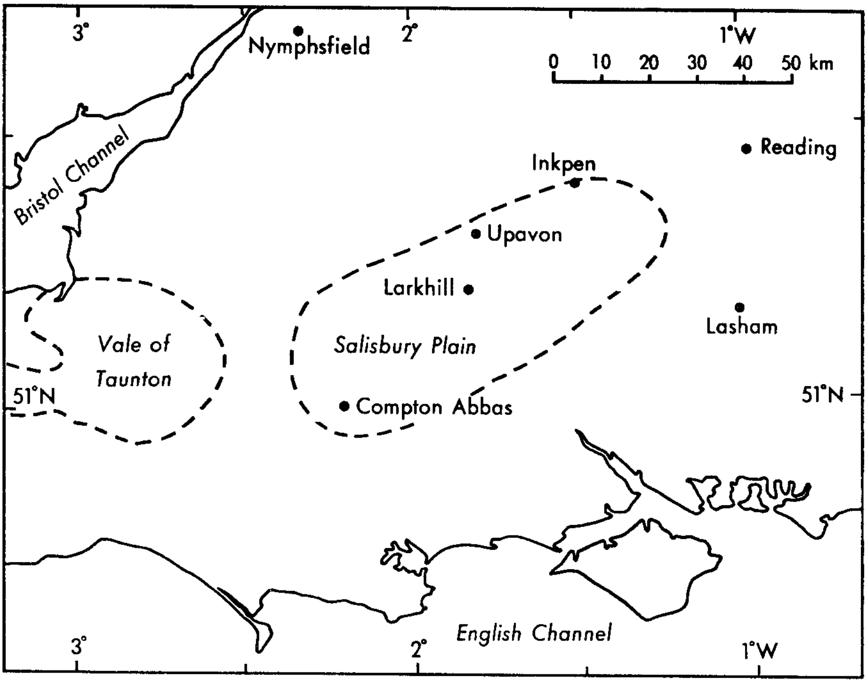

FIGURE 1—LOCATION OF PLACES REFERRED TO IN THE TEXT

Considering all the problems inherent in this type of exercise it was felt that the best approach would be to analyse those days which gave weak thermals, and those which gave strong thermals. Days of weak thermals were defined as those on which all the reported values of W were $<1\cdot5$ m/s and launches were made to coincide with the time of maximum temperature; days of strong thermals were days for which one or more of the reported values of W exceeded 3 m/s*.

Data on thermal conditions were available for 50 days, 13 being classified as good, 11 as poor and 14 as moderate days. Thermal activity was inhibited on the remaining days by layer cloud. The weather on the majority of days was broadly similar, with early mist or stratus quickly clearing to give clear skies or small amounts of shallow cumulus. Thickening cirrus probably brought thermal activity to a premature halt on three good days. Mean surface winds were never greater than 7 m/s.

One drawback in relying on a limited number of gliders in this type of investigation is that the area to be explored is necessarily limited. Since thermals can be notoriously inconsistent even on good days, it is possible that on some occasions thermal conditions have been underestimated.

* On one of the days when the maximum reported value of W (W_{max}) was 3 m/s, evidence became available of stronger thermals at Nymphsfield and Lasham, to the north-west and south-east respectively of Inkpen. Exceptionally therefore this day was also classified as a good day. It may be that other days when W_{max} was reported as 3 m/s could also have been associated with larger values elsewhere, but in the absence of positive evidence they were not included in the sample of good days.

Relationship between environmental temperature curve and thermal strengths

On considering the problem from several different angles it became apparent that the basic shape of the temperature profile at dawn between the ground and about 2000 m had a major influence on the eventual value of W_{max}.

Strong inversions, subsidence or nocturnal, which affected levels up to about 700 m agl and limited the upward penetration of dry adiabatic lapse rates from surface temperatures during the morning, were characteristic of the representative temperature profile on 10 of the 11 poor days. Subsidence and nocturnal inversions were also present on some of the good days but none of the bases of these subsidence inversions was below 1300 m agl. An attempt to quantify the effects of these inversions on the types of thermal day was made by carrying out a simple discriminant analysis on a parameter δN_H defined as the difference between the potential temperature of the surface night minimum and the potential temperature at a height of H m agl on the representative sounding. This was done for a selection of values of H. (In practice this is equivalent to adding $H/100$ K to the temperature at height H m agl before subtracting the minimum surface temperature to obtain δN_H.) A measure of the discriminant properties of δN_H for each H is given by the ratio of the difference in mean values of δN_H for the sample of good days (M_{HG}) and for the sample of poor days (M_{HP}) divided by the average of the standard deviations (σ_{HG} and σ_{HP}) of the values of δN_H on the good and the poor days respectively, i.e. by

$$2(M_{HG} - M_{HP})/(\sigma_{HG} + \sigma_{HP}).$$

Results are summarized in Table I, which shows an orderly change of the discriminant ratio with H and an extreme value for the ratio of 2·3 at H = 1000 m. When used as a discriminant, δN_{1000} allocates days with values above 9·9 K to poor, and those with values below 9·9 K to good, thermal days. On this non-independent sample δN_{1000} incorrectly allocates only one of the 24 days.

Table I—Discriminant measures of δN_H for five values of H

	δN_{300}	δN_{750}	δN_{1000}	δN_{1500}	δN_{2000}	No. of days
Good days						
Mean (a)	4·81	6·08	6·92	8·92	12·38	13
Standard deviation (b)	2.31	2·51	2·59	3·33	2·44	13
Poor days						
Mean (c)	6·27	9·88	11·14	12·91	15·00	11
Standard deviation (d)	2·94	1·64	1·12	1·95	2·61	11
(a) − (c)	−1·46	−3·80	−4·22	−3·99	−2·62	
(b) + (d)	5·25	4·15	3·71	5·28	5·05	
Ratio $\frac{2\{(a) - (c)\}}{(b) + (d)}$	−0·56	−1·83	−2·27	−1·51	−1·04	

Where

$\delta N_{300} = \theta_{300} - \theta_{min}$ at 300 m agl etc.

θ_{300} = the potential temperature on the representative dry-bulb environment curve at 300 m agl.

θ_{min} = the potential temperature of the minimum surface temperature.

All values other than ratios and numbers of days are expressed in kelvins.

Although δN_{1000} so far appears to be a promising discriminant, inclusion of data from the 14 moderate days in the analysis showed that this parameter had little power to discriminate between poor and moderate or moderate and good days.

On the available evidence it is difficult to decide at what height an inversion ceases to have any great inhibiting effect on thermal formation. Inversions up to 700 m agl restrict thermal activity to the weak category, whilst an inversion above 1300 m has little restrictive effect on thermals. Limited experience suggests that moderate thermals (1·5–3·0 m/s) can develop even if there is an inversion with a base as low as about 1000–1100 m agl. When the bases of inversions are below this level thermals are usually weak.

Another attempt to quantify the effects of these inversions and temperature profiles was made by carrying out a similar form of discriminant analysis to that described above for δN_H on a parameter δD_H—defined as the difference between the potential temperature of the surface at the time of day-time maximum temperature (actual maxima were used, not forecast maxima) and the potential temperature at height H m agl on the representative sounding. Results are summarized in Table II.

TABLE II—DISCRIMINANT MEASURES OF δD_H FOR SIX VALUES OF H

	MAX–MIN	δD_{300}	δD_{750}	δD_{1000}	δD_{1500}	δD_{2000}	No. of days
Good days							
Mean (a)	11·54	6·73	5·46	4·62	2·54	−0·85	13
Standard deviation (b)	2·39	1·03	0·72	0·68	1·35	1·61	13
Poor days							
Mean (c)	12·36	5·91	2·14	1·23	−0·50	−2·64	11
Standard deviation (d)	1·23	2·52	1·43	0·61	1·60	2·36	11
Ratio $\frac{2\{(a)-(c)\}}{(b)+(d)}$	−0·45	0·46	3·09	5·26	2·06	0·90	

Where

δD_{300} = $\theta_{max} - \theta_{300}$ at 300 m agl etc.

θ_{max} = the potential temperature of the maximum surface temperature.

θ_{300} = the potential temperature on the representative dry-bulb environment curve at 300 m agl.

All values other than ratios and numbers of days are expressed in kelvins.

This also shows an orderly change in the discriminant measuring ratio with H and a maximum value of 5·3 for the ratio at H = 1000 m agl. This value of 5·3 is quite high, implying that the central values of δD_{1000} for good and for poor days are separated by some 5·3 of their own standard deviation units (i.e. by 2·6 of each of the two individual standard deviation units measuring the scatter of each sample). This shows that the discriminant power of δD_{1000} is substantially better than that of δN_{1000}. δD_{1000} used as a discriminant, between good and poor days only, allocates values above 2·8 K to good days, and values below 2·8 K to poor days. Assuming normal distributions of δD_{1000} for good and for poor days (plots on probability paper confirmed that both sets were well represented by normal distributions) and that the samples are representative, this value of 5·3 for the ratio implies that δD_{1000} would misclassify only about 0·5 per cent of these two populations. On this non-independent sample it achieves complete success in classifying the 24 days.

On the 13 days associated with strong thermals δD_{1000} was at least 3 K whilst on the 11 poor days it was not more than 2 K. However, again only good and poor thermal days have been considered and in practice the performance of δD_{1000} as a discriminant will be degraded because forecast values of the maximum surface temperature will have to be used rather than the actual values used in this investigation.

Indeed the degradation of performance will be quite sensitive to forecast errors of surface maximum temperature because the small values of the standard deviations of δD_{1000} on the two kinds of day contribute materially to the large discriminant ratio. δD_{1000} although apparently far superior in discriminant performance to δN_{1000} is considerably less robust. For example, errors of forecasting maximum temperatures with no bias but a standard deviation of 1 K would increase the standard deviations of δD_{1000} for both good and poor days to 0·2 K (assuming no correlation between the forecast errors and the scatters of δD_{1000}) and reduce the discriminating ratio to 2·8, implying a misclassification of some 8 per cent of the populations.

Inclusion of δD_H data for the moderate days at this stage of the analysis showed that δD_{1000} could be used to discriminate between poor and moderate, and moderate and good days, allocating values of δD_{1000} of less than 1·6 K to poor days and greater than 3·7 K to good days. On the non-independent sample δD_{1000} used within these limits gave the results shown in Table III.

TABLE III—RESULTS FOR δD_{1000} USED AS DISCRIMINANT ON THE NON-INDEPENDENT SAMPLE OF 38 DAYS

Observed	Forecast Good	Forecast Moderate	Forecast Poor	Total	Percentage correct	Percentage correct overall
Good	12	1	0	13	92	
Moderate	1	10	3	14	71	82
Poor	0	2	9	11	82	
Total	13	13	12	38		

Any factor reducing δD_{1000} will have an adverse effect on thermal formation. Experience has shown that areas of stratocumulus, medium-level cloud and even thick cirrus can inhibit thermals completely, although these do develop should breaks occur in any of the cloud sheets.

Even vigorous development of cumulus can itself inhibit the formation of thermals, especially when 'overconvection' occurs. ('Overconvection' is a term used in the gliding world to describe the spreading out of cumulus on reaching an inversion layer.) Conversely the lack of cumulus does not necessarily mean an absence of thermals, but merely that the thermal has not reached the condensation level.

Having established that for discriminating between good and poor thermal days 1000 m agl is the best level to use for both δD_{1000} and δN_{1000} and that δD_{1000} is a better discriminant than δN_{1000} it is tempting to produce a linear regression equation which could be used to forecast W_{max} from δD_{1000}. For this purpose variations between W_{max} on different days are somewhat reduced in value by the uncertainties associated with their determination, that is to say by the effects of variations in the rates of sink of the gliders, by differences in the numbers of observations of W available on different days from which to assess W_{max}, and by the style of some of the individual reports which were abbreviated to W_{max} in excess of some specified integral value of metres per second. Nevertheless values of W_{max} were assessed for each day of the sample of 38 days which have been categorized and a linear regression analysis carried out. This gave:

$$W_{max} = 0{\cdot}85\ \delta D_{1000} + 0{\cdot}5 \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

This equation had a standard error of estimate of W_{max} of 0·8 m/s on the sample whose values range from 0 to 5 m/s for W_{max} and 0 to 5·5 K for δD_{1000}. On independent data this performance is likely to be degraded and the performance in practice will also be degraded by the necessity of using forecast values of maximum temperature to obtain δD_{1000}. Assuming root-mean-square errors of 1 K for such forecasts and a degradation of about 25 per cent (of the 0·8) for independent data, a standard error of about 1·3 m/s is indicated for the likely performance of equation (1) in practice.

Independent data for the early part of summer 1975 were subsequently made available by a gliding club based at Upavon. Forecast values of the maximum vertical velocity ($\hat{W}_{max}$) were obtained by using equation (1) and δD_{1000} for the day in question, and these were compared with reported values of W_{max}. This gave root-mean-square errors of 0·8 m/s consisting of a mean error of 0·2 m/s ($W_{max} > \hat{W}_{max}$) with a standard deviation of 0·8 m/s.

The effect of advection

When assessing the likelihood of thermals an important point to be considered is how warm or cold advection will affect the existing air mass. Thus warm advection or subsidence will tend to inhibit thermals as the potential temperature at 1000 m agl increases, whilst cold advection enhances conditions. (German forecasters stress this aspect of thermal formation — T.A.M. Bradbury in a private communication.)

As examples, 14 and 15 August 1973 were two of the hottest days of the year with maximum surface temperatures around 29 °C. Despite this, thermals on both days were reported as weak; in fact the Inkpen-based gliders found no thermals at all on the 15th. The synoptic situation was typical of the type which produces high surface temperatures in summer with an east-south-easterly surface flow being maintained by a thundery low over France. The 09 GMT Larkhill ascent on the 15th (Figure 2) is representative of both days. δD_{1000} values were 1·5 K for the 14th and 2 K for the 15th, whilst δN_{1000} values were 11 K and 12 K respectively. On both days the development of the dry adiabatic to any great height was limited until after midday at which time the inversion near 700 m agl was broken. These are rather surprising results. Consideration of the environment curves in relation to dry adiabatics from surface temperatures would lead many forecasters to expect quite good thermals to develop in the afternoons after the inversions were broken. However, on both days gliding attempts were continued well into the afternoon without any good thermals being found. These were not circumstances when poor gliding conditions in the morning resulted in the cessation of observations by midday.

By way of contrast thermal conditions on 1 June 1973 were good, with many strong thermals. A cold front had crossed the country the previous night and the following ridge maintained north-north-westerly surface winds

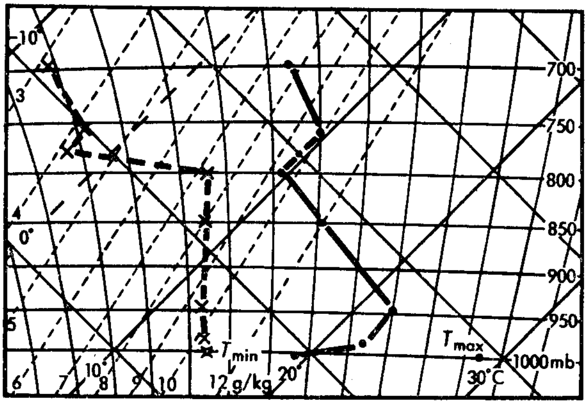

FIGURE 2—LARKHILL RADIOSONDE ASCENT FOR 09 GMT, 15 AUGUST 1973
· —— · dry-bulb temperature X – – – X dew-point temperature

of 5 m/s. The air was unstable to about 1500 m and dry, so only small amounts of cumulus developed. Because the cold front crossed the country late in the night the nocturnal surface inversion was very small, and easily destroyed as the temperature rose during the morning (Figure 3). At the same time cold air was flooding across the country, as the change in the Larkhill ascent shows (Figure 3). Here was a classic situation for strong thermals with dry air, rather limited instability, increasing surface temperature and cold advection aloft. δD_{1000} and δN_{1000} were both assessed as 5 K.

As a further step in the investigation, the heights to which dry adiabatics from the maximum surface temperatures could reach before intersecting the environment curves were also subjected to discriminant analysis. Results are shown in Table IV.

TABLE IV—DISCRIMINANT PROPERTIES OF h (HEIGHT IN METRES TO WHICH A DRY ADIABATIC LAPSE RATE FROM THE SURFACE MAXIMUM TEMPERATURE COULD RISE BEFORE INTERSECTING THE ENVIRONMENT CURVE)

	Mean	Standard deviation	No. of days
Good days	1840	270	13
Moderate days	1590	350	14
Poor days	1330	400	11

Discriminant ratios:	Poor–Good	1·5
	Poor–Moderate	0·7
	Moderate–Good	0·8

Considering just the poor and good days the value of 1·5 for the discriminant ratio is ill-established, quite poor, and implies (assuming normal distribution etc.) that some 23 per cent of the populations would be misclassified. In fact 3 of the 13 good days and 2 of the 11 poor days of this non-independent sample are incorrectly placed by h in the other category.

Sutton (1948) has shown that the greater the height to which a thermal can penetrate the stronger is W. More recently Lindsay (1970), in a study of glider flights made in the United States of America, found a convenient

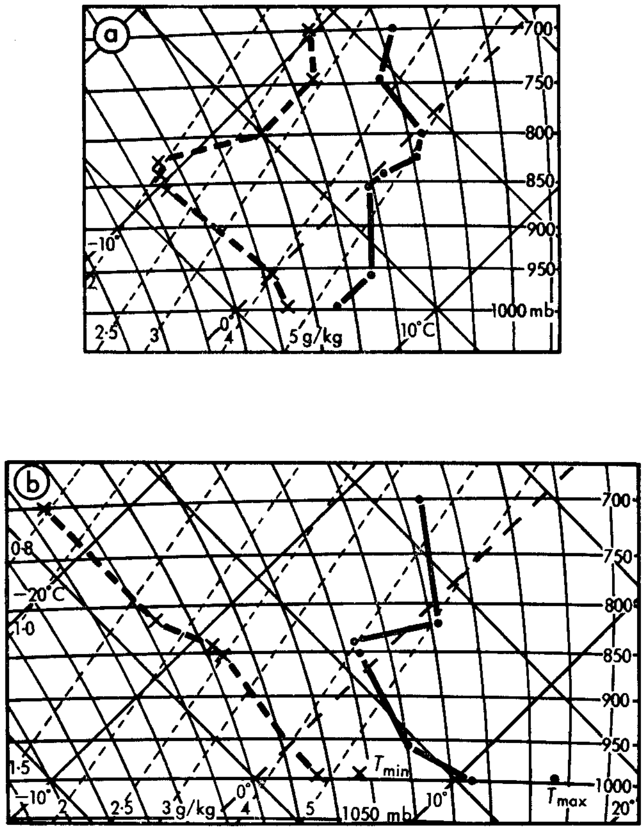

FIGURE 3—LARKHILL RADIOSONDE ASCENTS ON 1 JUNE 1973
(a) 05 GMT before cold advection
(b) 09 GMT after cold advection
· —— · dry-bulb temperature X – – – X dew-point temperature

relationship to exist between W_{max} and the vertical extent of dry adiabatic (or neutral) conditions, but his findings are not entirely consistent with observations of thermals over southern England, the greatest difference being that the maximum vertical velocities found in this country appear to be much stronger than those discussed by Lindsay. Why this is so is hard to explain, but possibly the poor performance of the American glider has some bearing on the difference. For example according to Lindsay's data extension of neutral conditions up to 2000 m would be associated with thermals of 2 m/s, whereas over southern England this kind of situation produced thermals of 4–5 m/s.

Lindsay's data, which appear on his published graph relating to W_{max} and the height to which dry adiabatic conditions extend, were also subjected to discriminant analysis for subsamples of good and poor days (Lindsay's W_{max} of $\geqslant$2·5 m/s and $\leqslant$1·5 m/s were used to define subsamples of 10 good and 8 poor events respectively). This gave a discriminant ratio of 1·9, rather better

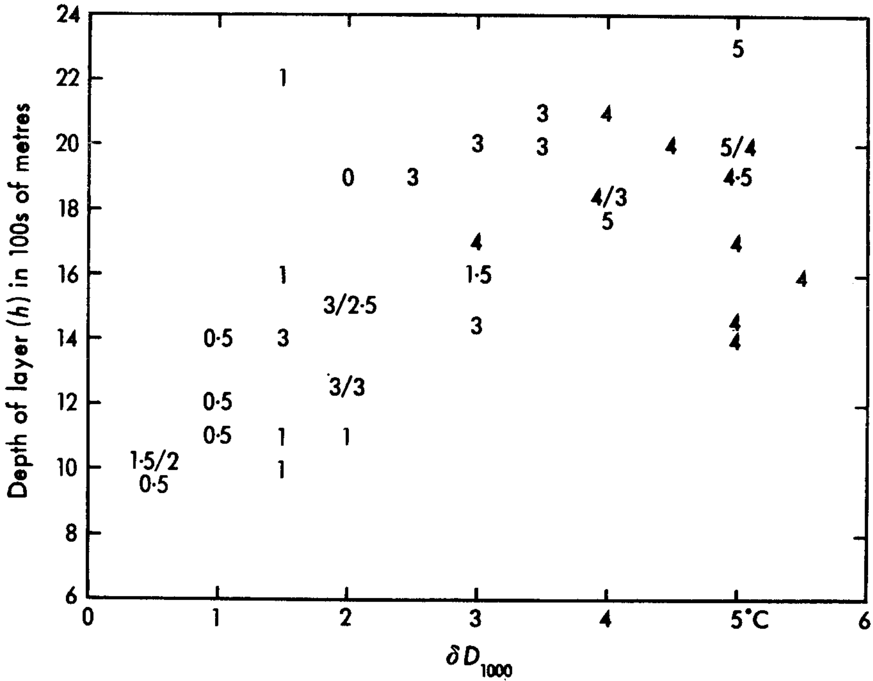

FIGURE 4—RELATIONSHIP OF OBSERVED MAXIMUM VERTICAL VELOCITY W_{max} TO DEPTH OF DRY ADIABATIC LAYER (h) AT T_{max} AND δD_{1000}

(3/4 indicates two values of W_{max} obtained from separate flights.)

than for the present sample, but not as good as δN_{1000} or δD_{1000} (even when the latter is degraded by the effects of errors of forecasting maximum temperature of 1 K standard deviations).

Thus even though the mean values of h increase with larger values of W_{max} (Figure 4), the poor performance of h as a discriminant is disappointing. It may be that on occasion the method of constructing a dry adiabatic on the tephigram is unrealistic and that instead of using the observed surface temperature as a starting point, as has been done in this investigation, a lower temperature should be used. For example on 15 August the 12 GMT ascent for Crawley shows evidence of a high lapse rate in the surface layers and a dry adiabatic lapse rate which has its base at a temperature of some 1·5 to 2 K below the observed surface temperature (Figure 5). On the assumption that these conditions also existed over Salisbury Plain, then the dry adiabatic at maximum surface temperature would have its base at 27·5 °C instead of 29 °C and h would be about 900 m. This value of h would then be consistent with the poor gliding conditions found on this day.

Figure 4 also shows that on this sample no good days occur with h less than 1400 m agl.

It is interesting that when considering discriminant properties of δN_H and δD_h for good and poor days the best discriminant ratios emerged for H = 1000 m agl. Evidently environmental temperatures in the vicinity of 1000 m

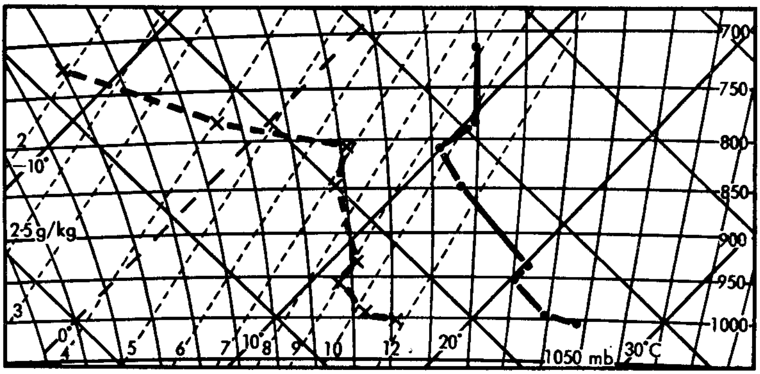

FIGURE 5—CRAWLEY RADIOSONDE ASCENT FOR 12 GMT, 15 AUGUST 1973

· —— · dry-bulb temperature X – – – X dew-point temperature

agl before modification by solar heating have a special significance from the point of view of the formation of thermals. Perhaps this is associated with some characteristic depth of the atmosphere necessary for strong thermals to be able to form. It may be relevant that Pearson and McGregor (1976) by use of a numerical model have shown that for convection in a neutral environment a lid to the top of the boundary layer will influence the upward velocity of a temperature perturbation well before it reaches the level of the lid. It may also be relevant that in Johnston's (1958) method for forecasting temperature rise, the thickness of a layer which is changed from an isothermal to a dry adiabatic state by maximum insolation over southern England is about 1000 m from April to September.

COMMENCEMENT AND CESSATION OF THERMAL ACTIVITY

As would be expected from previous discussion thermal activity started earliest on unstable days at various times between 0900 and 1030 GMT, with one exception, and persisted until between 16 and 18 GMT. On poor days thermals started after 12 GMT and, again with one exception, ceased by 1630 GMT. Since gliders were not usually airborne until mid-morning it is possible that thermal activity could have started earlier than the times reported. On the basis of the information available, thermals only became strong and frequent enough to enable a glider to remain airborne on an unstable day if dry adiabatic conditions extended up to at least 800 m. That thermals do develop with a shallower adiabatic layer is evidenced by the weakness of the thermals that develop on stable days. Even so the dry adiabatic had to penetrate to at least 500 m, and on most occasions 600 m, and be associated with the breakdown of the inversion before sufficiently strong thermals developed to permit gliding. Once thermals had formed they were usable at heights below 800 m agl; in fact experienced glider pilots claim to have contacted thermals as low as 100–150 m agl although at this level they are very weak.

The early cessation of thermals on stable days was not entirely unexpected. On average the diurnal air temperature change is at a maximum at the surface and decreases with altitude (Johnson, 1929). There is also a small lag effect so maximum air temperatures tend to occur slightly later as higher and higher levels are considered. This effectively creates the beginnings of a nocturnal inversion and is the mechanism whereby thermals begin to become less frequent. The weaker the thermals are at the time of their maximum development the earlier they cease.

In favourable conditions in high summer isolated thermals have been found over southern England as late as 19 GMT, but in most cases the main period of activity can be considered to have ceased by 18 GMT.

A mechanism which destroys thermals is the influx of sea air behind the sea-breeze front. In the sea-breeze circulation δD_{1000} is reduced as relatively cold sea-air can eventually reach a depth of some 700–800 m near the coast; a similar depth to that of the inhibiting subsidence inversion (McCaffery, 1966). Following the onset of the sea-breeze the air near the coast is constantly replenished by the cool sea-air, thus restricting any further temperature rise (Watts, 1955). This cooling effect of the sea-air diminishes inland, but even so aircraft observations across a sea-breeze front between Lasham and Reading have shown a potential temperature difference of 1·5 K across the front (Simpson—private communication). Because the sea-air arrives at inland areas near maximum temperature it accelerates the process which reduces thermal activity. It is believed that thermals useful for gliding do not usually develop in the sea-breeze air.

Stubble fires

During the latter part of summer stubble fires are a source of strong thermals, even when thermals formed naturally are very weak. Vertical velocities in these thermals can be very high and have been known to exceed 10 m/s (Lever—private communication).

Additional comment

The flights discussed in this paper were made over some excellent soaring country. Owing to the nature of the terrain other areas are notoriously poor for thermals, for example the poorly drained rather flat Vale of Taunton, and even on the best days activity over such terrain will be relatively weak.

Conclusion

It could be argued that the sample used in this investigation is too small to be used to formulate any hard and fast rules for forecasting thermals. Nevertheless the results are consistent in themselves and agree with the general impression gained from descriptive literature. The performance of equation (1) on the independent data is especially encouraging. Thus, broadly speaking, thermals will start as the adiabat approaches 800 m agl, but if this depth of penetration is limited until midday or later thermals will be weak. If δD_{1000} exceeds 3 K then it is unlikely to be a poor day for gliding. Obviously each case should be given careful consideration and special thought given to the effects of advection and any element which inhibits any temperature rise.

In practice pilots are usually content with a statement that thermals will be weak (>0, $<1{\cdot}5$ m/s), moderate ($\geqslant 1{\cdot}5$, $\leqslant 3$ m/s) or strong (>3 m/s). Sensible use of δD_{1000}, h and Figure 4 aided by equation (1) should enable such forecasts to be made on a sound basis.

ACKNOWLEDGEMENTS

I would like to thank my colleagues at Upavon for the helpful suggestions they have made during discussion on this subject, and Mr C. L. Hawson of Meteorological Office Headquarters, Bracknell for his guidance, particularly with the statistics. Especially I would like to thank Mr P. Cottrell and his associates at Inkpen for their infinite patience, and all those who have been good enough to write to me privately.

REFERENCES

BROWNE, I. C., DAY, G. J. and LUDLAM, F. H. 1955 Observations of small shower clouds. *Met Mag*, **84**, pp. 72–76.

GOLDNEY, P. 1970 Some observations of thermals. *Weather*, **25**, pp. 147–150.

GRANT, D. R. 1965 Some aspects of convection as measured from aircraft. *Q J R Met Soc*, **91**, pp. 268–281.

JAMES, D. G. 1954 Fine scale characteristics of the lowest 5,000 ft of the atmosphere as observed from an aircraft. *Met Res Pap* No. 875.

JOHNSON, N. K. 1929 A study of the vertical gradient of temperature in the atmosphere near the ground. *Geophys Mem* No. 46.

JOHNSTON, D. W. 1958 The estimation of maximum day temperature from the tephigram. *Met Mag*, **87**, pp. 265–266 *and two following art pages.*

LINDSAY, C. V. 1970 Air mass type and season favoring long cross-country soaring flights over the eastern United States. *Schweizer Aerorevue*, **45**, pp. 81–85.

MCCAFFERY, W. D. S. 1966 Comments on techniques for forecasting the sea-breeze. *Forecasting Techniques Branch Memorandum* No. 12, pp. 23–43.

MURGATROYD, R. J. 1954 Investigations of cumuliform cloud (Meteorological Office Discussion). *Met Mag*, **83**, pp. 208–215.

PEARSON, R. A. and MCGREGOR, J. L. 1976 An open boundary condition for models of thermals. *J Atmos Sci*, **33**, pp. 447–455.

REID, D. G. and WU, A. Y.-K. 1965 The diurnal variation in the depth of the convection layer. *Schweizer Aerorevue*, **40**, pp. 605–606 and 649–651.

SCORER, R. S. 1954 Bubble convection. *Met Mag*, **83**, pp. 202–208.

SIMPSON, J. E. 1966 The sea-breeze at Lasham. *Forecasting Techniques Branch Memorandum* No. 12, pp. 3–7.

SUTTON, O. G. 1948 Convection in the atmosphere near the ground. *Q J R Met Soc*, 74, pp. 13–30.

WALLINGTON, C. E. 1961 Meteorology for glider pilots. London, John Murray, Chapter 13 (Convection), pp. 149–170.

WATTS, A. J. 1955 Sea-breeze at Thorney Island. *Met Mag*, **84**, pp. 42–48.

WICKHAM, P. G. 1966 Weather for gliding over Britain. *Weather*, **21**, pp. 154–161.

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REPORT ON THE SUMMER SCHOOL IN SATELLITE METEOROLOGY HELD IN ALPBACH, AUSTRIA FROM 3 TO 12 AUGUST 1977

By R. W. LUNNON
(Meteorological Office, Bracknell)

1. Introduction

The summer school was initiated and co-ordinated by the Austrian Solar and Space Agency (ASSA) and other bodies involved in its organization and sponsorship were CNES* (France), DFVLR (Germany), ESA, NTNF (Norway), SBSA (Sweden) and SNG (Switzerland). The summer school was one of a series on various aspects of space science—in 1978, for example, there is to be one on Spacelab. This probably explains why the sponsoring bodies were all space research organizations rather than meteorological services or research organizations. However, both the lecturers and the students came from a wide variety of institutions and represented a broad spectrum of interests—there were two oceanographers, for example. Nationally, German-speaking (i.e. including Austrian) numbers exceeded the rest, and although I was the only representative of a British organization others whose native tongue was English were a Canadian working for a NATO oceanographic research establishment in Italy, a representative of the UK branch of the office of US Naval Research, and John Morgan of the European Space Agency who until recently was a member of the Meteorological Office.

The subjects lectured on and studied in workshops (perhaps 'practicals' would be a better word to use) could be broadly split up into four categories: the present observational system, the usefulness of satellite observations and the First GARP Global Experiment (FGGE); software and hardware necessary for processing satellite data; interpretation of satellite imagery; and remote sounding of the atmosphere. These are the subjects of the four following sections; a fifth is given over to impressions.

One lecture which did not fall into any of the above categories was given by D. Nikoden (ECON, New Jersey, USA) on the economic benefit of improved meteorological forecasts to the Florida citrus industry. Attempts to estimate economic benefits of weather forecasts are numerous but I have not heard of other assessments of the effects of improved forecasts. The experiment is in progress, the 'control' trials utilizing the relatively poor forecast having taken place in the winter of 1976/77 and the trials utilizing what it is hoped will be improved forecasts being intended to take place in the following two winters. (The improvements will be partly due to the employment of satellite data, apparently by using window-channel infra-red data to estimate land-surface temperatures.) There are all sorts of problems with this kind of study—for example, if it is announced that there has been a widespread severe frost the market price of citrus fruit increases and if the frost is not as severe as had been announced then clearly the growers have benefited although it is not clear whether there has been an overall economic benefit. It appeared

* See the Appendix for an explanation of these and subsequent sets of initials.

that the improved forecast would be accompanied by improved publicity—for example, satellite-derived actual surface temperatures would be shown on television weather forecasts—and it would be difficult to decide whether the economic benefits were due to the improved forecast rather than to the improved publicity. Nevertheless it was interesting and encouraging that such a study was being attempted, even if the only outcome was the knowledge necessary to carry out an improved study in the future.

2. The usefulness of satellite data in the present observing system

B. Bolin (University of Stockholm) gave two lectures which discussed the data requirements of numerical general-circulation and climatic models. Ideas such as predictability, and experiments to simulate observing systems were described and emphasis was placed on measurements which were not needed for operational forecasts but which were needed for climatic studies such as cloudiness, radiation balance, and amounts of trace gases.

A. Piaget (Swiss Meteorological Institute, Zurich) gave a talk on the data requirements for synoptic and numerical forecasting in which it was stressed that appropriate interpretative techniques should be devised to make the best use of satellite data.

P. Morel (CNES, France) talked about the use of satellites for tracking drifting sensors in the atmosphere and ocean, and the use to which the data from such experiments have been put.

I. Haupt (Free University of Berlin) reviewed the operational satellites flown in polar orbits, with emphasis on the present NOAA series, and also discussed the instruments to be flown on the TIROS-N series.

D. Lennertz (ESA, Toulouse) introduced METEOSAT and explained its history and T. Mohr (Deutscher Wetterdienst) explained the role of geostationary satellites in FGGE, giving a brief survey of the evolution of the latter.

3. Description of hardware and automatic data processing

C. Honvault and J. Antikidis (both from ESA, Toulouse) described in some detail the METEOSAT system and the processing of image data once they had reached the ground.

P. Bernadet and M. Taillade (CNES, France) described the ARGOS system, which will be on board the TIROS-N series of satellites, for locating and collecting observations from drifting sensors (buoys and balloons).

K. Zimmermann (Central Office for Meteorology and Geodynamics, Vienna) spoke on the subject of reception and storage of image data, his talk being a fairly general one, with reference to particular satellites only by way of illustration.

J. Gredel and W. Ratten (DFVLR) described the system being developed at Oberpfaffenhofen to process geostationary satellite imagery interactively—to give the user the option of examining any subset of a sequence of images on a user-specified scale, both spatial and temporal. (The system would operate using archive tapes for the case being studied, these tapes having been obtained by the user from ESA.)

K. Richter (Technical University of Graz) spoke on the subject of satellite instrumentation, giving a historical review before talking in some detail about the instruments to be flown on NIMBUS G.

P. Louis (ESA, Toulouse) gave a review of ESA studies for future meteorological satellites. A few eyebrows were raised at the estimated cost of such systems, even though the cost was less than that of METEOSAT.

4. Image interpretation

M. Debois (Dynamical Meteorology Laboratory, Palaiseau) spoke in general terms about methods of extracting winds from satellite images, describing in more detail the optical methods used at his establishment.

F. Cayla and L. Fusco (ESA, Darmstadt) described the method to be used by MIEC for METEOSAT data, including the preliminary fully automatic processing of arrays of pixels* to determine the general properties of the cloud field in view. Workshop 5 was devoted to an attempt to extract winds manually from a sequence of cloud images, and a discussion of the problems involved, for example the representativeness of cloud motions of the wind field.

I. Haupt (Free University of Berlin) talked on her group's work which uses images in the visible spectrum to map the changes in sea-ice distribution in the North Atlantic and in neighbouring sea areas. Her attempts to correlate sea-ice distribution with synoptic features were regarded somewhat sceptically but undoubtedly the analysis of sea-ice distribution had been very thorough.

H. Rott (University of Innsbruck) spoke on the use of LANDSAT and VHRR data for determining snow cover in the Alpine regions. This is a subject of great importance for the Austrians and there was a reasonable correlation between snow cover, as determined from cloud photographs, and spring-time melt runoff. Workshop 3 was given over to this subject—techniques for assessing snow-lines are fairly subjective so this was a useful introduction to the problem. In the Alps it is necessary to know the height of the ground above sea level before one can relate images with large zenith angles to their true position on the earth's surface—this was not a problem that I had encountered before!

V. Meise (Central Office for Meteorology and Geodynamics, Vienna) gave a most illuminating lecture on the application of satellite images to synoptic weather forecasting. Several cases were presented comparing, for example, cloud photographs with charts of 1000–500 mb thermal vorticity, there being marked correlation for this particular case. This theme was the subject of Workshop 2 in which the relationship between cloud photographs and synoptic features was stressed.

G. Warnecke (Free University of Berlin) demonstrated motion pictures made from satellite images. These illustrated the point that there is a danger of trying to use too much data—the most informative movie-loops comprised a sequence of perhaps three or four images each of which was a relatively small segment from the full earth disc. Some cases were shown in which the time sequence was run backwards so that, for example, a readily identifiable fully developed mid-latitude depression could be traced back to a stage where it was less easy to recognize but important to pick out for forecasting purposes.

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* The smallest resolvable element of an automatically processed image has come to be known as a 'pixel'.

5. Interpretation of sounding data

E. Raschke (University of Cologne) spoke on the subject of the determination of local and global energy budgets from satellite measurements. A major problem was how to get a representative sample, in both space and time, and satellite orbits with fairly low angles of inclination (50° for example) were suggested for coverage of the tropics.

H. Bolle (University of Innsbruck) spoke about the radiative transfer equation and the determination of atmospheric transmission functions. One aspect covered in some detail was the use of empirical formulae to describe the variation of transmission with pressure, temperature and amount of absorber. Workshop 6, organized by Bolle, looked at the topic of retrieving cloud top and surface temperatures from window-channel infra-red radiance measurements, in which the parametrization of the atmospheric contribution is a major problem.

H. Fischer (University of Munich) spoke on the problems of retrieving temperature profiles and non-uniform absorber amounts from infra-red radiances. This was mostly fairly familiar, although ozone profiles from satellite measurements were relatively new to me. In Workshop 1, organized by Fischer, we used Chahine's relaxation method to retrieve a temperature profile from radiance measurements; this was instructive for me as not only had I never used Chahine's method (it being considered more or less obsolete nowadays) but also I had never done a retrieval by hand, and it was interesting actually to handle the numbers involved.

K. Kuenzi (University of Berne) talked about the problems of sensing atmospheric liquid-water and water-vapour content using passive microwave sensors. Two wavelengths, both responding to both liquid and gaseous water content, but in different proportions, were used. However, the emissivity of the sea surface is variable and it was considered necessary to know either the sea state or the water content of the atmosphere, and to use the microwave measurements to determine the other variable. Note, though, that microwave water-vapour sensors respond to total optical depth of water vapour whereas infra-red channels respond to distribution of water vapour.

P. Kopke (University of Munich) talked on the use of satellite measurements to determine the optical depth of atmospheric aerosols. The solar radiation scattered back to the satellite is a function of many other atmospheric parameters besides the optical depth and the choice of atmospheric conditions optimal for measurements and the best wavelength to use were discussed.

W. Ranger (DFVLR, Oberpfaffenhofen) spoke on the subject of a Spacelab-borne Lidar for atmospheric physics. In a sense all that he said was 'this is a Lidar and this is a Spacelab and we fly one on the other', the advantages and problems of flying instruments on satellites rather than operating them from the ground being fairly obvious. Workshop 4 was on the subject of the use of Lidar and acoustic sounder (Sodar) (ground-based) and was slightly disappointing, partly because the weather situation did not provide any particularily interesting applications for the experiments (for instance there was no inversion which we could try to detect with the Sodar).

6. Impressions and comments

I had expected that a European summer school held in the year of the launch of Europe's first meteorological satellite might have been dominated by

METEOSAT topics, but this was not the case, partly no doubt because Austria is not participating in the ESA METEOSAT program. Nevertheless it was useful to hear from the ESA contingent exactly how they intended to extract from the imagery the various parameters that they intend to transmit to users. Bearing in mind the cost of METEOSAT, and the effort that is being put into the processing of its data, it is to be hoped that potential users show patience and tolerance towards what is basically a new observational device in the hands of relatively inexperienced operators.

Naturally it was disappointing to me that relatively little work is being done by those European institutions represented at Alpbach in the field in which the High Atmosphere Branch of the Meteorological Office is involved, namely the retrieval of atmospheric parameters from infra-red and microwave sounding data. Nevertheless it was interesting to see what information people were managing to extract from satellite images—visible, infra-red and microwave; it is suggestive that this is an area in which the Office lags behind Europe, or at least behind those countries represented at Alpbach.

Although there was relatively little research overlap between myself and the other students on the course it was interesting to discuss with them the set-ups of their own institutions. It was also interesting to see how other institutions engaged both in research and in forecasting (of which there were few) attempted to integrate them; for example, one Swede I spoke to spent three days a week doing research and two days on the bench.

APPENDIX

CNES	= Centre National des Études Spatiales = National Centre for Space Studies
DFVLR	= Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt = German Aerospace Research and Testing Institute
ESA	= European Space Agency
GARP	– Global Atmospheric Research Program
METEOSAT	= (European) Meteorological Satellite
NATO	= North Atlantic Treaty Organization
NTNF	= Norges Teknisk-Naturvitenskapelige Forskningsråd = Royal Norwegian Council for Scientific and Industrial Research
SBSA	= Swedish Board for Space Activities
SNG	= Schweizerische Naturforschende Gesellschaft = Swiss Scientific Research Society
VHRR	= Very High Resolution Radiometer

REVIEW

The ocean–atmosphere system, by A. H. Perry and J. M. Walker, 245 mm × 190 mm, pp. xi + 160, *illus.*, Longman Group, London, 1977. Price £5·50 (paperback).

This is one of the few books to deal with atmospheric and ocean systems together, with the emphasis on their interaction and interdependence. It is intended as a text for second and third year undergraduates in geography, geophysics, and environmental science, for marine biology courses and nautical and maritime studies, as well as being a reference book for research workers in the field.

The introductory chapter on the nature and characteristics of the ocean–atmosphere system includes an interesting historical background. In Chapter 2, called 'Ocean Macro Circulations', the general circulation of the atmosphere is first outlined. The causes of ocean currents are then discussed. The circulation of the Indian Ocean is described in detail, including its response to the reversal of the prevailing surface winds during the Asian Monsoon. Some theoretical aspects of the Gulf Stream are presented. Other topics include the extension of the Gulf Stream and its effect on our climate, the Arctic and Southern Oceans, the formation of bottom water, deep-water circulations and the importance of the thermohaline circulation.

Waves, swell, drift currents and storm surges are among the topics treated under 'The action of wind on sea'. The characteristics of waves are explained using simple formulae, although more complex treatments are referred to. Ekman theory is used to explain the phenomenon of upwelling. Chapter 4 is concerned with ocean–atmosphere heat exchange. The budgets of heat and radiant energy are discussed in detail, with reference to the general circulation. Transfer of heat to the atmospheric boundary layer is examined, then convection on various scales, along with a miscellany of subjects such as sea fog and the formation of sea ice.

In Chapter 5, entitled 'Thermal behaviour of the ocean atmosphere and climatic responses', sea surface temperatures and their variations are discussed. The persistence of sea surface temperature anomalies and their effect on the atmosphere, together with more complex coupled air–sea systems, are reviewed. Finally there is an outline of the possible contribution of ocean–atmosphere interaction to climate changes. The last chapter contains a useful summary of various international research projects and their aims, followed by a very brief section on some advanced numerical climate models.

The book is clearly set out, and follows a logical overall pattern. It is more a review than a textbook, the authors quoting extensively from the literature. The subject matter on the whole is well chosen, comprehensive and up to date. Observational rather than theoretical studies are emphasized. Mathematics, where included, has been reduced to a minimum by quoting the relevant formulae and referring the reader to appropriate sources for the derivation. Almost all the figures are taken or adapted from original papers, greatly enhancing the book's value as a work of reference. However, a few diagrams are not quite in tune with the text, or have inadequate captions.

The book fulfils its aim as a text for undergraduates, being much more than an elementary introduction, yet not requiring an extensive background in mathematics or fluid mechanics. There are more than 500 references, about half of which were published during the last decade, and they include many review papers. Thus the book may also prove useful to research workers, even though there is a very sparse coverage of numerical modelling.

J. F. B. MITCHELL

THE AKROTIRI TRAGEDY

At 0630 Cyprus time on 7 December 1977 a U2 aircraft of the United States Air Force, monitoring the Arab/Israeli ceasefire in Sinai, crashed on take-off at Akrotiri, destroying the Main Meteorological Office and the RAF operations Centre. The total of five who were killed immediately all died in or near the the meteorological office; they were locally employed meteorological assistants (Mr A. Televantos and Mr C. Hanni), a radio operator (Mr P. Gostinian), the office cleaner (Mr A. Tanayia) and the United States pilot of the aircraft. Mr J. A. Flawn, Senior Scientific Officer, who was the duty forecaster at the time of the accident, was severely burned and died from his injuries thirty-six hours later. Two other radio operators in the Meteorological Communications Centre (Mr M. Michaelides and M. A. Passades) received serious burns and Mr Michaelides has since been transferred to the Princess Mary's Hospital at RAF Halton. The RAF authorities arranged for Mrs Michaelides to stay at Halton with her husband.

A fund was established for the dependants of the locally entered staff involved in the accident and by the end of the year the response from the Office had resulted in the collection of over £1550, illustrating the strength of the special relationship which has been established over the years between United Kingdom and Cypriot staff. The fund is being administered by a small committee in Cyprus. Separate consideration is being given to an appropriate memorial for Mr Flawn. It is thought that the Akrotiri accident is the first to involve loss of life on duty, outside the Second World War, since Mr M. A. Giblett, Superintendent of the Airship Services Division of the Office, was killed in the R101 accident near Beauvais in France on 5 October 1930.

Mr Flawn's funeral, attended by many of his friends and colleagues, was held at New Quay, Dyfed, on 17 December 1977. Mr F. H. Bushby, DD Met O(F) represented the Director-General.

The Commander of the Royal Air Force Element in Cyprus wrote to the Director-General soon after the accident noting the outstanding way in which Mr F. P. Sims, Principal Meteorological Officer at Akrotiri, and his staff had dealt with the many personal and operational problems which were produced.

The Director-General had written immediately following the accident to the families of all the bereaved. The Air Attaché from the United States Embassy in London visited Mrs Flawn in New Quay and Mrs Michaelides at Halton shortly before Christmas to express personally the sympathy of the United States Government.

The site of the Akrotiri office is being completely cleared and a new Main Meteorological Office is to be established nearby as an integral part of the RAF Operations Centre.

THE METEOROLOGICAL MAGAZINE

NO. 1267 FEBRUARY 1978 VOL. 107

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NOTICES

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1 monthly **Annual subscription £13.14 including postage**

Dd. 497684 K15 2/78

ISBN 0 11 724796 0
ISSN 0026–1149

Met.O.915

METEOROLOGICAL OFFICE

the meteorological magazine

MARCH 1978 No 1268 Vol 107

Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.915

THE METEOROLOGICAL MAGAZINE

No. 1268, March 1978, Vol. 107

523.4

THE ATMOSPHERES OF THE PLANETS*

By B. J. MASON
(DIRECTOR-GENERAL, METEOROLOGICAL OFFICE)

I am deeply honoured to be giving this year's Halley Lecture in memory of one of the greatest scientists of the seventeenth century, eclipsed perhaps only by Newton himself. I have no real qualifications for this task because, although Halley did write an important paper in 1686 on the structure and origin of the trade winds and monsoons, and contributed substantially to the study of meteorological optics and the aurora, his outstanding contributions were in fields of which I have little real knowledge. But Halley was always ready to tackle new subjects, and this opportunity has encouraged me to escape temporarily from the more pressing problems of the Earth's atmosphere and study the atmospheres of Venus, Mars and Jupiter. The subject is timely because our knowledge has increased greatly during the last few years through measurements made by American and Russian spacecraft during close approaches to all three planets and through landings on Venus and Mars. Because of the great differences in their physical parameters (see Table I) and in the relative importance of dynamical, radiative and thermodynamical processes, the meteorology of the three planets is entirely distinct and very different from that of the Earth.

VENUS

Some general features. Although Venus, our nearest planetary neighbour and the brightest planet in the sky, has a mass and radius very similar to those of the Earth, the constitution of its atmosphere and its meteorology are completely different.

Venus is the nearest planet to the Sun to possess an atmosphere. This is more than 100 times as massive as the Earth's atmosphere and is composed almost

* A written version of the Halley Lecture for 1977 which was delivered in Oxford on 17 May 1977; this paper is a modified form of one with the same title published in the December 1977 issue of *The Observatory* (*London*).

TABLE I—BASIC PARAMETERS OF THE PLANETS

	Venus	Mars	Jupiter
Mean distance from the Sun (10^6 km)	107	226	773
Sidereal period	225 days	687 days	11·86 years
Rotation period about axis	—243 days	1·03 days	9 h 55½ min
Mass (relative to Earth)	0·81	0·11	318
Radius (km)	6050	3380	71 350 (equator)
Mean density (g/cm^3)	5·1	3·97	1·33
Surface gravity (m/s^2)	8·90	3·70	26
Solar irradiance (W/m^2)	2600	600	10
Effective radiation temp. (K)	230	216	130
Average surface pressure	90 bar	7–8 mb	20 bar } arbitrary reference level
Average surface temp. (K)	760	230	400 } arbitrary reference level
Cloud cover (per cent)	100	5	100
Albedo	0·77	0·20	0·42
Adiabatic lapse rate (K/km)	10·5	4·4	1·9
Scale height (km)	5	11	17
Atmospheric composition	CO_2 traces HCl, HF, CO, H_2O	CO_2 traces H_2O, O_2, CO, A, Kr	Mainly H_2 He, CH_4, NH_3, PH_3
Cloud composition	droplets H_2SO_4	water ice	ammonia crystals particles of NH_4SH, water and ice
Radiative relaxation time (s)	10^9 (surface) 10^5 (80 km)	2×10^5	$\approx 10^8$
Dynamical relaxation time (s)	6×10^6 (surface) 2×10^5 (80 km)	8×10^3	5×10^3

entirely of carbon dioxide. The incoming solar energy flux of 2600 W/m^2 nearly twice that received by the Earth, is largely trapped by the carbon dioxide to produce very high surface temperatures of about 760 K. Observations of Venus, especially of its surface and lower atmosphere, have long been hindered by its unbroken layer of yellowish cloud whose top extends up to about 70 km above the ground and which reflects nearly 80 per cent of the incident sunlight. This is in complete contrast to the Earth, which has an average cloud cover of only 50 per cent that reflects about 30 per cent of the incident sunlight. However, during recent years, our knowledge of the atmosphere of Venus has been greatly extended by observations from United States MARINER spacecraft (1971–72) which have orbited within 6000 km of the planet's surface and from the Russian VENERA probes (1969–73) which have penetrated the atmosphere itself.

Another remarkable feature of Venus strongly affecting its meteorology is its very slow period of rotation (243 Earth days) and the great length of day (120 Earth days) but, even so, the surface temperatures are remarkably uniform, with very little latitudinal or diurnal variation. This speaks for the efficiency of the atmospheric motions in transporting heat and reducing the temperature contrasts that would otherwise be impressed by differential solar heating. The radiative relaxation time (the time taken for a temperature perturbation to be reduced to 1/e of its initial value by radiative processes) is estimated to be very long, about 10^9 s, in the lower atmosphere, where atmospheric motions would achieve the same result in about 10^7 s. In the high atmosphere, in the upper parts of the cloud layer, the radiative and dynamical relaxation times are more nearly equal at about 10^5 s so that heat transfer by radiation and by the winds are more nearly equal. Moreover, since the radiative relaxation time near the surface is much greater than the length of day (10^7 s), the night-time does not last long enough for appreciable cooling to occur, and diurnal temperature effects are very small. By contrast, in the upper atmosphere, both latitudinal and diurnal temperature contrasts have an important influence on atmospheric motions.

Composition of the atmosphere. For many years the only gas definitely identified in the atmosphere of Venus was CO_2, discovered by Adams and Dunham in 1932, but recently HCl, HF, CO and H_2O have been detected spectroscopically in low concentrations. It is thought that whereas during the formation of the Earth's atmosphere, by the out-gassing of rocks, the CO_2 was largely dissolved in the oceans to form carbonates or used up in photosynthesis, on Venus the surface temperature was too high to allow condensation of water vapour or to support plant life, and so the CO_2 accumulated to form a high-density atmosphere that absorbed solar radiation by the greenhouse effect to produce the high temperatures now measured.

Water vapour was probably lost in the high troposphere in reactions with SO_2 and its derivatives to form droplets of H_2SO_4 (see later) and also, at higher levels, by photolytic dissociation, with the H_2 escaping to space. However, additional hydrogen may be produced at very high levels by the solar wind.

The variation in the number-density of cloud particles with height, as deduced from measurements of optical transmission by the VENERA 8 probe, is plotted in Figure 1. The particle concentration reaches a maximum value of rather more than $1000/cm^3$ at 45 km but falls off rapidly at lower levels to form a sharp cloud base at 30 km and more gradually at higher levels to form a diffuse cloud top at about 70 km. There is also some evidence for a lower, more tenuous cloud layer below 10 km.

Constitution and formation of the clouds of Venus. Detailed analysis of the polarization of reflected sunlight from the clouds reveals them to consist of spherical particles, probably liquid, of refractive index 1·44 and of remarkably uniform size with a mean radius of 1 micrometre. This uniformity of particle size, which appears to extend over the whole planet, is not characteristic of terrestrial clouds.

The cloud droplets most probably consist of 75 per cent H_2SO_4 and 25 per cent of H_2O, i.e. concentrated sulphuric acid, which would give a refractive index of 1·44 and, at the same time, account for the very low measured concentrations of water vapour (relative humidities of only 1–10 per cent in the vicinity of the cloud top). The infra-red spectrum of Venus, with a strong emission band at 11·2 micrometres, and the blackness of the planet at 4 micrometres, would also be consistent with the clouds being largely composed of H_2SO_4. The lemon-yellow hue of the clouds is, however, not so easily explained. This could be due to the solution in the droplets of a contaminant that absorbs blue light but, more likely, to particles of elemental sulphur. In fact, of the many possible substances examined in the laboratory, only solid elemental sulphur matches the absorption spectra of the clouds on Venus. Since it also absorbs strongly near the peak of the solar spectrum, a solid sulphur aerosol may play a significant role in the heating of the upper atmosphere.

The photochemical processes responsible for producing the cloud droplets of H_2SO_4, and which remove atomic sulphur from the atmosphere, are thought to occur mainly at heights above 65 km according to the following reactions:

$S + O_2 \rightarrow SO + O$

$SO + OH \rightarrow SO_2 + H$

$SO_2 + HO_2 \rightarrow SO_3 + OH$

$SO_3 + H_2O \rightarrow H_2SO_4$.

At the same time elemental sulphur may be produced by

$S + COS \rightarrow S_2 + CO$,

COS being formed at levels below 50 km and temperatures above 350 K, for example by

$S_2 + 2CO \rightarrow 2COS$.

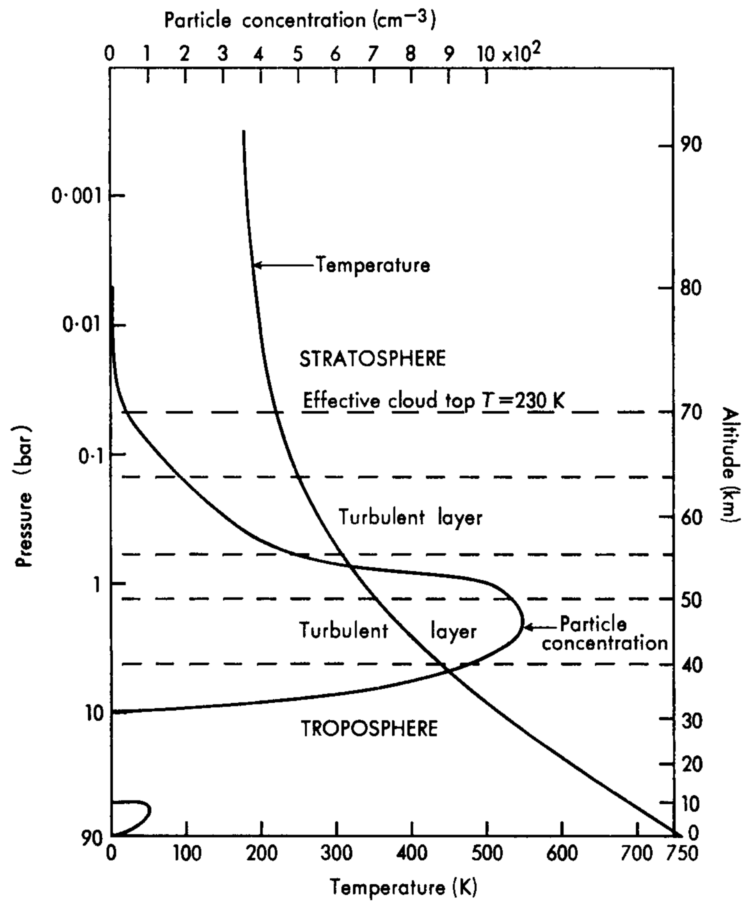

FIGURE 1—VERTICAL PROFILES OF TEMPERATURE AND CLOUD PARTICLE DENSITY FOR THE ATMOSPHERE OF VENUS

Droplets of concentrated H_2SO_4 would, of course, be much more stable than water clouds and would grow or evaporate much more slowly in response to vertical atmospheric motions than do terrestrial clouds. This may largely explain the unbroken and uniform character of the cloud deck on Venus. It has been suggested that the rapidly changing dark features revealed on ultra-violet photographs of the clouds mark the presence of ultra-violet-absorbing sulphur particles whereas in the bright areas the cloud droplets consist of almost pure sulphuric acid. If so, the dark features might mark regions of ascending convective motions bringing up from lower levels the COS required to form the elemental sulphur particles. High-resolution pictures of the planet's disc taken by the MARINER 10 television camera indicate the presence of tenuous haze layers high in the stratosphere at altitudes between 80 and 90 km. At least two distinct layers, separated by a few kilometres in altitude, appear in pictures taken both in orange and in ultra-violet light, and they extend laterally from the equator to high latitudes. If the particles are assumed to be transparent, with radius 1 micrometre, measurements of optical density would suggest number densities of the order of $0{\cdot}1/cm^3$.

The vertical structure of the atmosphere. The vertical temperature profile of the atmosphere of Venus, based on measurements of temperature, pressure and altitude made respectively with resistance thermometers, aneroids and capacitor sensors, and a pulsed radio altimeter on the VENERA probes, is shown in Figure 1. The temperature, 760 K at the surface, falls off linearly with height at the rate of 8 K/km up to 50 km, where it reaches 360 K, and thereafter more slowly to become nearly isothermal above 80 km (200 K). The lapse rate in the deep atmosphere is therefore less than the adiabatic value of 10·5 K/km.

The general shape of the temperature profile has been reproduced by radiative-transfer calculations involving the computation at successive levels of both the incoming solar radiation and the infra-red transfer. The net flux of solar radiation as a function of altitude and solar zenith angle, taking into account scattering and absorption by both aerosols and gases, is calculated in such a way as to be consistent with the VENERA 8 photometer measurements of the downward component of solar flux and the observed wavelength dependence of the planetary reflectivity (albedo). The size, concentration and nature of the cloud droplets and aerosol particles, assumed to occupy a layer between about 30 and 60 km, are chosen to be consistent with the optical and spectroscopic data described above. The net infra-red flux, and hence the radiative cooling and radiative equilibrium temperatures, is then calculated for each level. These procedures lead to temperatures that are much too high and also to too steep a lapse rate in the deep atmosphere but, when convective energy transport is introduced to bring the lapse rate down to the adiabatic value while maintaining radiative equilibrium at these levels, the resulting overall temperature profile for radiative–convective equilibrium agrees quite well with observation. The model calculations indicate that about 3 per cent of the incident solar radiation reaches the surface of the planet, compared with 1·5 per cent measured by VENERA 8, and this is sufficient to produce strong heating by the greenhouse effect and account for the observed high surface temperature.

The horizontal winds, observed by Doppler measurements of the radial velocity of the VENERA 8 probe, are plotted as a function of altitude in Figure 2. They increase steadily from only a few m/s in the deep atmosphere to about 50 m/s at 40 km and then rise quite sharply to about 100 m/s at 50 km. These winds are zonal in direction, blowing roughly along lines of latitude.

Atmospheric motions. Information on atmospheric motions has been provided by movements of cloud features seen in ultra-violet light as observed both from the ground and from MARINER 10, by Doppler shifts in reflected sunlight and in the CO_2 lines of the atmosphere, and by drift measurements of the VENERA probes as they entered the atmosphere.

Global views of the planet in ultra-violet light reveal dark Y- or C-shaped features near the equator, which vanish at one limb, and reappear at the other, suggesting a rotation period of about 4 days for the clouds. This implies a relative velocity between the clouds and the surface of about 100 m/s, which is very high compared with the slow rotation rate of the planet but is consistent with the strong zonal easterly winds, blowing in the retrograde direction of rotation of the planet, that were measured by VENERA 8 at altitudes above 50 km. In the low troposphere, below 10 km, the zonal velocities are only a few m/s and the meridional velocities are only about 2 m/s. Fluctuations in the radio signals received from the MARINER spacecraft indicated the existence of two layers of intense turbulence, each about 10 km thick, centred at about 45 km and 60 km with a preferred horizontal eddy size of about 5 km. The turbulence at 45 km may be caused by instabilities in a zone of strong winds and wind shear. The turbulent layer at 60 km is probably due to small-scale convection set up by strong solar heating of the cloud at this level but limited to a shallow layer near the tropopause by relatively stable layers above.

The 3400 photographs taken by MARINER 10 over 8 days, with resolution from about 100 m to about 130 km, revealed a subsolar disturbance (SSD) spanning some 20° of latitude and 80° of longitude, locked to the Sun–Venus line and continuously generated in response to maximum solar heating. The SSD shows cellular features, the largest of which are about 500 km across, with a good deal of interior structure. The cells, which last a few hours, move with the wind and change markedly from hour to hour, are almost certainly a manifestation of large-scale convection. The photographs also show a circumequatorial

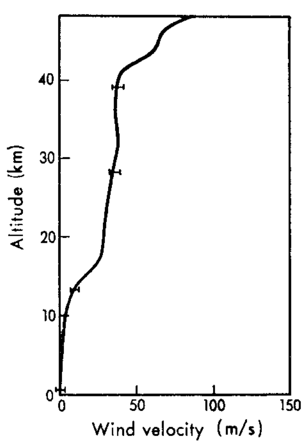

FIGURE 2—HORIZONTAL WIND VELOCITY MEASURED BY VENERA 8 AS A FUNCTION OF ALTITUDE

band containing cells of 100–500 km in diameter. These are also probably of convective origin, resulting from interaction between the high-pressure SSD and the zonal wind. Since the atmospheric pressure falls off from the SSD towards the poles, the zonal winds are accelerated towards high latitudes. The spiral streaks may perhaps be interpreted as associated 'jet streams'. The kinetic energy of these motions is eventually dissipated in the low-pressure polar vortices. In the virtual absence of Coriolis forces on Venus, temperature gradients may exist parallel to the zonal flow and hence parallel to the direction of the vertical wind shear. In this situation the flow may become unstable and break up into roll vortices with axes parallel to the mean flow, with wavelengths of the same order as the scale height (5 km) and growth times of a few days. Such instabilities, which probably account for the small-scale zonal streaks on the MARINER photographs, will draw energy from the mean flow, and thereby tend to destroy the shear and the horizontal temperature gradients and stabilize the vertical lapse rate.

Motions on the planetary scale. The driving force for the planetary circulation is the differential heating between the equator and the poles produced, in the upper atmosphere, by the differential absorption of solar radiation in the cloud layer and, in the lower atmosphere, by the residual radiation which reaches the planetary surface and produces high surface temperatures through the greenhouse effect. The intervening atmosphere is therefore heated both from above and from below. In the upper atmosphere, at cloud level, both radiative and dynamical processes are important in heat transfer and in reducing the horizontal temperature gradients whilst, in the deep atmosphere, the dynamical processes dominate. In the latter case the simplest circulation would be a convective cell with rising motions near the subsolar point and sinking motions near the antisolar point, similar to the Hadley cell of the Earth's tropical atmosphere. Such a circulation, depicted in Figure 3, would transport heat meridionally as well as vertically in a direction depending on the static stability. The cell will transport heat polewards only if the gradient of potential temperature is positive, i.e. $\theta_1 > \theta_2$, so that the mean lapse rate is rather less than the adiabatic value, as is observed to be the case. Detailed analysis, based on the assumption that dynamical heating (or cooling) of the air due to the vertical motions is balanced by radiative cooling (or heating) when averaged vertically and latitudinally, leads to reasonable values for the horizontal and vertical gradients of potential temperature and shows that the Hadley circulation could maintain a lapse rate close to the adiabatic value without the help of small-scale convective or turbulent heat transfer. In these conditions of near static stability, the Hadley cell produces temperature differences between pole and equator of only about 0·1 K. These very small temperature gradients, and the fact that the lapse rate is nearly adiabatic, speak for the efficiency of the motions in redistributing the heat even though the zonal and meridional winds in the lower atmosphere are only of the order of 1 m/s and the vertical motions are only about 1 cm/s.

The vertical extent of the Hadley circulation in the atmosphere of Venus is not known, nor the extent to which it is linked to the stratospheric circulation. The latter, being driven by the absorption of most of the incident solar radiation in the cloud layers at about 50–60 km altitude, shows the influence of diurnal heating, and is apparently quite distinct from the tropospheric flow. The main problem is to explain the rapid motion of the cloud features which both Doppler and VENERA probe drift measurements show to be due to real winds of about

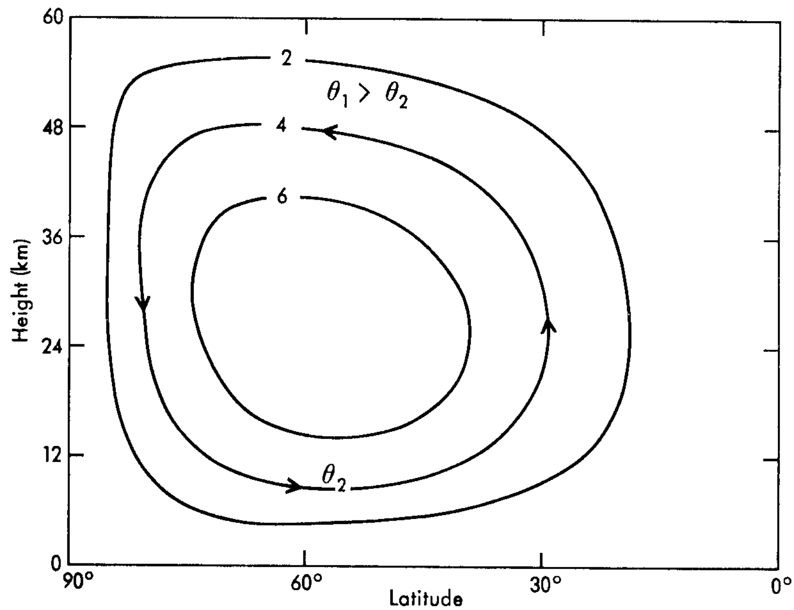

FIGURE 3—A POSTULATED HADLEY-CELL CIRCULATION FOR THE LOWER ATMOSPHERE OF VENUS

100 m/s travelling in the opposite direction to, and 20 times as fast as, the overhead motion of the Sun relative to a fixed point on the surface.

The most likely explanation for this strong 4-day circulation is the so-called 'moving-flame effect' proposed by Schubert and Whitehead. If a flame or other compact heat source is moved in a circular path beneath a pan of liquid*, motions are induced as shown in Figure 4. The moving source induces a thermal wave which lags behind the source by an amount which increases with height above the bottom of the fluid because of the finite time required for the heat to be conducted upwards. This produces tilted convection cells giving a net motion at the top of the fluid which is opposite to the direction of motion of the heat source. This portrays what might be expected to happen in the atmosphere of Venus if it were heated from below. In fact the heating occurs mainly in the upper atmosphere in the cloud layers so that the thermal lag, being greatest at the lower levels, might be expected to produce an opposite tilt of the cells and a net motion in the *same* direction as the Sun. However, a more detailed analysis by Plumb shows that the direction of tilt depends rather critically on the static stability, and in the stable upper atmosphere of Venus where internal gravity waves are probably responsible for the vertical transport of heat, the cells should indeed tilt so as to produce a net motion in the opposite direction to that of the Sun. Moreover, the theory indicates that mean motions much faster than the

* This experiment was first suggested by James Thomson in his 1892 Bakerian Lecture to the Royal Society following a much earlier but incorrect suggestion by Halley (1686) that the Trade Winds on the Earth were caused by the diurnal revolution of the Sun from east to west over the equatorial zone.

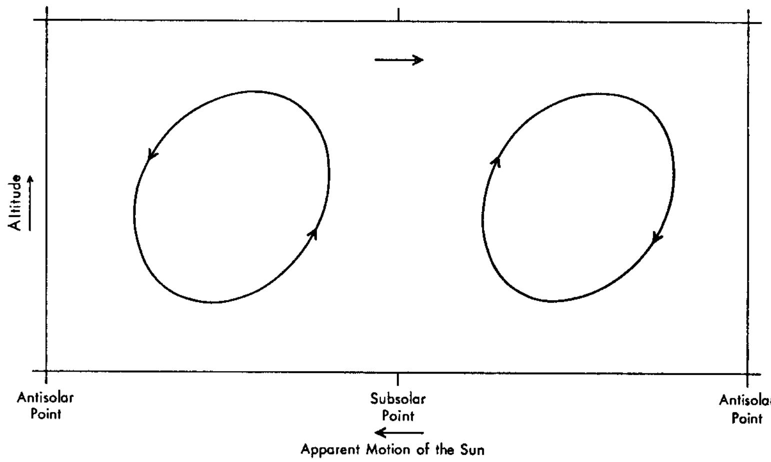

FIGURE 4—THE VERTICAL CIRCULATION TO BE EXPECTED IN AN ATMOSPHERE HEATED FROM BELOW BY A MOVING HEAT SOURCE

speed of the heat source may be generated, and that this magnification factor is independent of the length of the solar day but is largely determined by the deviation of the vertical lapse rate of temperature from the adiabatic value and by the distribution of radiative heating and cooling in the planetary atmosphere. Strong zonal retrograde motions of about 100 m/s are reproduced at heights of about 60 km in a three-dimensional, 16-level model of the atmospheric circulation of Venus described recently by Young and Pollock (*J Atmos Sci*, **34**, 1977, pp. 1315–1351). The model produces planetary-scale waves and eddies in the high atmospheres, initially as a result of the meridional temperature gradient and the slow rotation of the planet. The large eddies release potential energy that is apparently converted into mean zonal kinetic energy through a non-linear instability which thereby amplifies the planetary waves and zonal winds.

It is planned that in December 1978 a United States PIONEER spacecraft will land on Venus and that a second craft will be inserted into an elliptical orbit passing within 200 km of the surface every 24 hours. This second vehicle will carry an infra-red spectrometer supplied by the Atmospheric Physics Department of Oxford University which, in measuring emissions from CO_2 in the 15-micrometre band, will provide atmospheric temperature profiles from the outer fringes of the atmosphere down to the top of the cloud deck. Global daily maps of the temperature field should reveal new information on planetary atmospheric wave motions, including the 4-day rotation, and increase considerably our knowledge and understanding of the upper atmosphere of Venus.

MARS

Mars, about half the diameter of the Earth, has a very tenuous atmosphere composed mainly of CO_2 which, exerting a total pressure of only 6–8 mb, has less than 1 per cent of the mass of the terrestrial atmosphere. The incoming solar flux of 600 W/m^2, about half that received by the Earth, experiences little absorption in the atmosphere and, with only 20 per cent reflected by the planetary surface, implies a mean equilibrium temperature of 216 K, in reasonable agreement with direct measurement. During the winter months a thin sheet of cloud, the so-called 'polar hood', composed of ice crystals, gradually spreads from the polar regions to middle latitudes. During the remainder of the year the planet is mainly free of cloud but the surface is sometimes obscured for a month or more at a time by dust veils raised from the surface by the wind.

Our knowledge of the Martian atmosphere and of its surface, including the polar ice caps, has been greatly extended in recent years by observations from the United States MARINER spacecraft and especially by the VIKING landing vehicles.

Composition and temperatures of the Martian atmosphere. The Martian atmosphere is composed largely of CO_2, with H_2O, CO, O_2 as minor constituents whilst, in the upper atmosphere, traces of A, Kr, Xe, O and NO have been detected by mass spectrometers carried on the VIKING spacecraft.

The temperature of the atmosphere below 30 km (0·1 mb) was determined during the descent of the VIKING V2 which landed at 48°N, 226°W, carrying an infra-red thermal radiometer to measure the thermal emission of CO_2 in several narrow channels in the 15-micrometre band. This remote method of temperature sensing was checked by direct measurements in the lower atmosphere and on the surface. The vertical temperature profile, as deduced from such measurements made on an early summer morning after the lower atmosphere had cooled overnight by radiation, is plotted in Figure 5, the altitude of the vehicle being measured by a radio altimeter. The atmosphere is seen to be isothermal from 1·5 to 4 km, and thereafter the temperature falls not quite linearly with increasing height with an average lapse rate of about 1·3 K/km. The vertical temperature profile, as determined by infra-red remote sensing from orbiting spacecraft, exhibited waves of wavelength 15–25 km, the amplitude of which grew with increasing altitude to reach about 25 K at 90 km. These are thought to be gravity waves excited by diurnal heating and cooling of the planet's surface and lower atmosphere. The temperatures of the lower atmosphere in summer are too high to allow condensation of CO_2, so that the haze seen at middle latitudes in the northern summer is probably caused by the condensation of water vapour.

At levels above 100 km the mass spectrometers on VIKINGs V1 and V2 measured the densities of CO_2 from which vertical profiles of temperature were deduced up to heights of 200 km from the hydrostatic equation. The measured densities of N_2 and A also yield vertical profiles of the eddy diffusion coefficient over the same height range. The atmosphere is well mixed to heights in excess of 120 km, with eddy diffusivities a hundred to a thousand times larger than those obtaining at similar heights above the Earth. The upper atmosphere was found to be surprisingly cold and variable, with average temperatures well below 200 K and reaching a minimum of about 130 K at 130 km. These temperatures are significantly lower than those derived from airglow observations made from MARINER spacecraft when Mars was near perihelion.

Surface weather. At the VIKING 2 landing site the air temperature 1·6 m above the ground showed strong seasonal and diurnal variations. In late summer, when temperatures were highest, the mean daily temperature was 223 K with maximum and minimum values of 263 K and 185 K respectively. The mean diurnal range was 240 K to 190 K. In May, when the temperatures

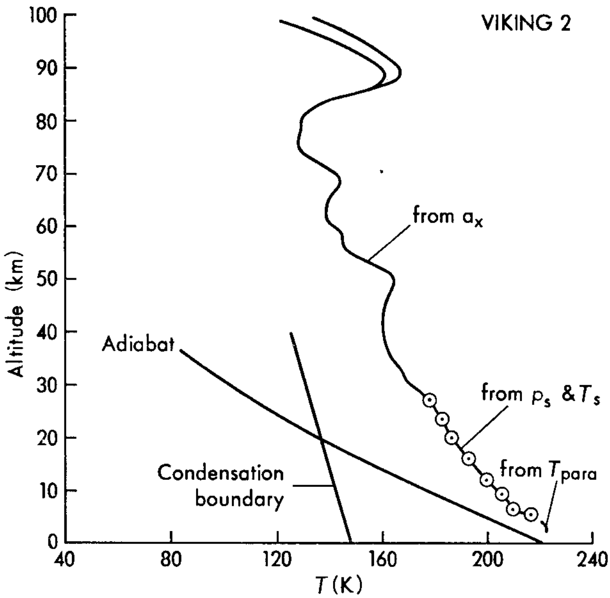

FIGURE 5—VERTICAL TEMPERATURE PROFILE OF THE MARTIAN ATMOSPHERE AS MEASURED BY VIKING 2 DURING ITS DESCENT TO THE PLANETARY SURFACE

The temperatures above 30 km (marked a_x) were derived from readings of accelerometers on the spacecraft. At lower levels they were inferred from direct measurements of pressure (p_s) and temperature (T_s) made from the spacecraft, while T_{para} refers to measurements made on the parachute supporting the craft on its final descent.

were lowest, the mean daily value was 163 K with extremes of 190 K and 150 K. In winter, the surface temperatures were low enough to produce night-time frosts of solid CO_2 which disappeared in the day time.

In summer the winds were rather constant from day to day. The daily mean vector wind was 0·7 m/s from the south-east with a diurnal amplitude of 3 m/s. The winds became gusty after sunrise and remained so until mid-afternoon as the lowest layers became convectively unstable. Peak gusts were 17 m/s. The winds were generally too light to raise dust, but observations from the MARINER 9 orbiting spacecraft suggested that the winds are much stronger in winter. The surface pressure at the VIKING 2 site varied between 7 and 8 mb with a diurnal range of 0·3 mb. The large seasonal variation may have been partly due to the condensation of a substantial fraction of the CO_2 on the polar cap.

The Martian polar ice cap. More than 700 high-resolution photographs taken of the north polar ice cap by VIKING 2 in October 1976 revealed the central area to be covered by layered deposits. The areas of the caps expand greatly to about 55° latitude in the local winter but contract again to about 85° in the summer. The long-standing controversy of whether the caps are composed mainly of water ice or of solid CO_2 has now been settled beyond all reasonable doubt by measurements from MARINER 9 and VIKINGs V1 and V2. According to the V2 measurements of the strength of the 1·38-micrometre emission band of water vapour, the total column densities reached a maximum value at 70–80°N in the northern midsummer equivalent to 75 micrometres of precipitable water. This requires near-surface temperatures above 200 K which, together with the fact that the residual ice cap had a brightness temperature of 205 K, is incompatible with the survival of a cap of solid CO_2 which would require a surface temperature below 150 K at a total surface pressure of 6 mb. Thus the residual (summer) ice cap must consist largely of water ice the thickness of which is estimated to be between 1 m and 1 km. However, the reflectivity of the residual cap was appreciably less than that for clean terrestrial snow, suggesting that it was mixed with a good deal of dust.

During the local winter, when surface temperatures fall as low as 125 K, condensation of both water vapour and CO_2 is possible, so that the greatly expanded caps consist of a mixture of water ice and solid CO_2. An upper limit to the quantity of water ice that may be deposited on the polar cap is set by the total atmospheric water vapour in the winter hemisphere. This is equivalent to about 20 micrometres of precipitable water which, if spread uniformly over a cap covering 1 per cent of the hemisphere, would produce a layer 2 mm thick. Much of this would evaporate in the summer and perhaps be transported to the other polar cap.

It seems likely that the water-vapour content of the Martian atmosphere is maintained by a large reservoir of water ice in the form of a permafrost layer which, in winter, covers most of the planet but which, in the spring and summer, slowly recedes towards the poles releasing substantial quantities of water vapour into the atmosphere.

Atmospheric circulation of Mars. Because of its small mass, the Martian atmosphere responds rapidly, by radiative and convective processes, to changes in the surface temperature. The characteristic radiative response time being only about two days compared with 100 days on Earth, the large-scale atmospheric motions are under strong solar control. However, because the atmosphere is so tenuous, heat transport by the winds is inefficient and so large temperature contrasts exist. Complicating factors in the dynamics of the planetary circulations are the release of latent heat when CO_2 and water vapour condense to form the polar caps, and the raising of dust palls that affect both the thermal balance and the stability of the atmosphere.

Pollock, Leovy and Mintz have adapted a simplified numerical model of the Earth's atmosphere to the Martian atmosphere assumed to consist of pure CO_2 and to be initially isothermal at 200 K and at rest with a surface pressure of 5·8 mb. The circulation is thermally driven as a result of convective and infrared radiative heat transfer associated with the latitudinal variation of surface temperature. The model allows CO_2 to condense when the surface temperature falls below the frost-point, the thermal effects of the latent heat released and the reflectivity of the advancing ice cover being taken into account. In solstitial conditions, the model predicts strong zonal westerly winds in the middle latitudes of the winter hemisphere increasing in strength from 20 m/s near the surface to more than 60 m/s at 10 km altitude. They develop long standing waves induced by the larger mountains and also, as a consequence of the strong meridional temperature gradients between latitudes 20° and 60° (the edge of the ice cap), cyclonic and anticyclonic disturbances similar to those observed on Earth. Other features are a strong thermally driven mean meridional circulation across the equator, but only weak easterlies over much of the summer hemisphere.

Dust storms on Mars. A typical dust storm develops in three phases. In Phase 1, which lasts about 5 days, the storm begins as bright spots or cores with diameters of less than 400 km and which show signs of diurnal regeneration with overnight decay. Phase 2, lasting for 5–30 days, and which may be accompanied by the appearance of blue-white peripheral clouds and the development of secondary bright cores at new locations, is the expansion phase. The dust veil spreads first in the E–W direction, encircles the whole planet in less than 20 days, and then sometimes spreads polewards to cover most of the planet in 20–30 days. Finally in Phase 3, the decay phase, clearing usually starts near the poles and spreads to lower latitudes.

There are evidently favoured sites for the development of the bright cores, notably the elevated plateaux between latitudes 20° and 40° S. They tend to occur just before the southern-hemisphere solstice, which is close to perihelion. Measurements of CO_2 pressure by infra-red detectors on the MARINER 9 orbiter showed the Hellas basin to be full of a dust pall for about 30 days before the great dust storm of 1971. Television pictures showed that dust became well mixed in the vertical direction up to heights of at least 30–40 km; infra-red radiometers indicated that this caused major changes in the vertical temperature profiles, which became almost isothermal, consistent with strong absorption of solar radiation by the suspended dust.

It seems that the dust storms tend to start in the southern hemisphere just before the solstice at a time when the Leovy–Mintz model predicts only weak easterly winds over much of the hemisphere. These would probably not be strong enough to raise dust, but local enhancement by thermal tides and topographic features may produce local winds and small vortices capable of raising sufficient dust to be responsible for the first phase of the storm. Phase 2 is then assumed to occur when the strong cross-equatorial cell builds up to maximum strength near the solstice, giving winds capable of raising large quantities of dust over a wide area. The radiative effects of the dust pall reduce the vertical temperature gradient thereby stabilizing the atmosphere, weakening the circulation and initiating the decay phase of the storm.

An alternative explanation by Gierasch and Goody invokes a feedback mechanism whereby an incipient dust storm generates its own high winds, thus enabling the storm to grow and become self-sustaining. The starting conditions are assumed to be an extensive low-level dust pall with light general winds and strong solar heating. Provided that there is some pre-existing cyclonic vorticity in the flow, and that the site is far enough from the equator for the Coriolis force to be an important influence, cyclonic inflow within the boundary layer will produce vertical motion which will raise the top of the dust cloud. Solar heating of the dust then raises the temperature, reduces the surface pressure and increases the vorticity. Intensification continues until the vortex can raise dust unaided by the weaker background circulation, and during this phase there will be diurnal regeneration and overnight relaxation. During the next stage the strong vortex continues to raise dust until settling from the stratosphere fills the lower atmosphere over a wide area. Horizontal temperature gradients then weaken and the storm enters the decay phase.

JUPITER

General features. Jupiter, having a mean density of only 1·33 g/cm^3, is composed almost entirely of light elements, probably in their primordial abundance, with hydrogen predominant. Since the outer layers of the planetary mass are fluid, there is no sharply defined material surface, but the density increases with depth and the pressure at the centre of the planet is estimated to be about 3×10^7 bar. Under these conditions the core probably consists of liquid metallic hydrogen, the conductivity and motion of which produce the observed strong planetary magnetic field.

Jupiter is enveloped in three layers of cloud suspended in a deep and well-stirred atmosphere composed largely of hydrogen and helium. The measured effective radiative temperature of the upper cloud deck, having an average reflectivity of 0·42, is 130 K. This is about 30 K higher than would be produced by the incoming solar flux of only 10 W/m^2 and suggests the presence of an internal heat source of about the same strength as the solar radiation. The total mass of the atmosphere is much greater than that of the Earth, the pressure 100 km below the upper cloud layer being 10 bar and the temperature about 350 K.

An important dynamical feature of Jupiter is its rapid (supersonic) rate of rotation, the length of day being only 10 hours. The atmosphere is therefore dynamically rather than thermally controlled, sustaining only small horizontal and diurnal temperature differences.

Our present knowledge of the Jovian atmosphere rests largely on observations made by the PIONEER 10 and 11 spacecraft during the nearest approaches to within about 10^6 km in December 1973 and December 1974.

Composition of the Jovian atmosphere. The Jovian atmosphere is composed largely of hydrogen. Helium was first detected by PIONEER 10 in November 1973. The measurements indicated an He/H_2 ratio of 0·18—very close to the solar value—suggesting that the planet has a composition similar to that of the primordial nebula. The evolution of the atmosphere has probably been slow because of the low temperatures existing at high levels (150 K at 200 km), and the fact that the planet is so massive that even the hydrogen is able to escape only very slowly. Other gases that have been detected are water, ammonia and methane, with traces of ethane, acetylene and phosphine. Analysis by ground-based spectroscopy of the infra-red bands in the sunlight reflected from the clouds gives column densities, assuming a common level of line formation ($p = 1{\cdot}7$ bar, $T = 200$ K) that corresponds to the top of the water cloud. The ratios of the abundances of the major constituents H_2, CH_4 and NH_3 are consistent with the atmosphere's having a solar composition, which would require the abundances shown in Table II.

TABLE II—RELATIVE NUMBER DENSITIES CORRESPONDING TO SOLAR COMPOSITION

Constituent	H_2	He	H_2O	CH_4	NH_3	H_2S
Number density (per cent)	88·6	11·2	0·1	0·06	0·015	0·003

Of the compounds featured in Table II, only H_2S has not yet been detected in Jupiter's atmosphere. The strength of the H_2O lines in the 5-micrometre infra-red window suggests a humidity mixing ratio of about 10^{-6}, the saturation vapour pressure at the top of the water-cloud layer being very low. Such a low concentration would suggest a thousandfold depletion of water vapour on Jupiter relative to the solar abundance. However, the distribution of water vapour does not appear to be uniform over the planetary disc, and the measurements are probably not yet sufficiently reliable for such conclusions to be drawn with confidence.

Constitution and formation of Jovian clouds. On the assumption that the Jovian atmosphere is effectively mixed to great depths with a temperature lapse rate that is adiabatic, it is possible to compute its chemical composition as a function of altitude. The simplest model, developed by Lewis and his collaborators, assumes that the atmospheric species are in thermochemical equilibrium below the tropopause (p = 100 mb, z = 160 km, T = 100 K). Starting with a parcel containing more than 50 volatile constituents in solar abundance at a reference level of $p = 2 \times 10^5$ bar, T = 2000 K, this is allowed to ascend adiabatically, and the levels at which the various liquid and solid phases condense out are calculated, making due allowance for the latent heats released. The condensates are assumed to remain as aerosols at these levels. For example, quartz is calculated to precipitate at temperatures below 1500 K, whilst ammonium chloride, bromide and iodide are condensed below 460 K. The densest clouds, of water and ice, are calculated to form at T = 270 K, 60 km above the 'surface' reference level where p = 20 bar. Near the 200 K (90 km) level, H_2S is thought to react with NH_3 to form a cloud of solid NH_4SH particles and to provide the main source of particulates in the atmosphere. Finally, white crystals of ammonia precipitate at 155 K (p = 700 mb, z = 120 km) to produce the visible upper cloud layer, this being confirmed by the appearance in Jupiter's emission spectrum of lines characteristic of solid ammonia. It is, however, important to realize that the predictions of the models are quite sensitive to the assumed concentrations of the various species, and that if these are changed significantly, large changes in the predicted cloud structure may result. Thus if the concentrations of NH_3, H_2O and H_2S are all increased five-fold, the predicted cloud bases are lower, the clouds much denser, and aqueous ammonia condenses out at 300 K to form a cloud of liquid droplets beneath the water/ice cloud with base at 270 K.

In general there is good agreement between the abundances calculated from the models and those estimated from spectroscopic data except that the model produces about 10^3 times as much water as the observations suggest, and that H_2S has not been detected experimentally. Moreover, the model calculations so far described provide no explanation for the marked coloration of Jupiter. For these additional features it seems reasonable to look to irreversible chemical reactions caused perhaps by photolysis, lightning discharges etc.

It is possible that the observed ethane and acetylene are produced by the ultra-violet photolysis of methane. While at high levels most of the H_2S is probably removed by condensation with NH_3 to form the cloud of NH_4SH particles, at levels below 90 km (T = 200 K) it may well be dissociated by ultraviolet light, so initiating the following reactions leading to the production of elemental sulphur:

$$H_2S + h\nu \rightarrow HS + H$$

$$HS + HS \rightarrow H_2S + S$$

$$\text{or} \qquad \rightarrow H_2 + S_2.$$

The sulphur would then be available for further reactions leading to hydrogen polysulphide H_xS_y, or ammonium polysulphide NH_xS_y, which are generally yellow, orange and brown in colour and may therefore account for some of Jupiter's colours. The coloured bands, usually brown tinged with blue, tend to coincide with the latitudinal belts that are free of the upper white ammonia-crystal cloud where the ultra-violet radiation could perhaps penetrate to the intermediate layer of NH_4SH cloud and photolyse the H_2S quite efficiently.

The existence of phosphine, PH_3, is difficult to explain if the atmosphere were to contain as much water as the models predict, because most of it would be oxidized to form P_4O_6 which would dissolve in the water cloud droplets. However, if the water content were three orders of magnitude smaller, as suggested by the observations, this would probably be insufficient to oxidize more than a small fraction of the PH_3. If then phosphine is present above the level of the ammonia-crystal cloud, it is likely to be dissociated by ultra-violet light and eventually produce red phosphorus crystals according to:

$$PH_3 + h\nu \rightarrow PH_2 + H$$
$$PH_2 + PH_2 \rightarrow PH_3 + PH$$
$$PH + PH \rightarrow P_2 + 2H$$
$$P_2 + P_2 \rightarrow P_4,$$

which could conceivably account for the colour of the Great Red Spot, the top of which rises several kilometres above the general level of the ammonia-crystal clouds.

Vertical temperature profile of Jovian atmosphere. Measurements by infra-red radiometers on the PIONEER vehicles give a mean effective radiative temperature for the planet of 130 K on both the dark and sunlit sides, which speaks for rapid heat transport by the atmospheric motions and very small diurnal temperature changes. Moreover, the measurements show that the planet emits about twice as much energy as it receives from the Sun. The additional heating is believed by some to be produced by a slow contraction of the planet—a rate of only 1 mm/year would apparently suffice. This extra heat is radiated outwards from the planetary 'surface' through the atmosphere, so that Jovian meteorology is largely internally driven.

The temperature structures of the atmosphere above the $p = 1$ bar, $z =$ 110 km level, as deduced from measurements on the infra-red emission bands of H_2, NH_3 and CH_4, made both from Earth and from the PIONEER vehicles, agree in locating a temperature minimum of about 100 K at the 100 mb, 160 km level. Above this the temperature rises in the stratosphere to reach 150 K at 10 mb (see Figure 6). The derived pressure at the 130 K level is 0·48 bar, with $T = 165$ K at $p = 1$ bar. The vertical temperature profile below $p = 1$ bar, derived mainly from microwave (1–20 cm) emissions of NH_3 and infra-red emissions of H_2 (about 5 micrometres), is nearly linear, with a mean lapse rate of about 2 K/km. These measurements are quite consistent among themselves and allow a model adiabatic atmosphere of solar composition to be followed down to at least the $p = 20$ bar, $T = 400$ K level, which we may arbitrarily define as the 'effective surface' of the planet.

There is also consistency between cloud-free radiative models, which show most of the infra-red flux to be emitted from levels between 700 and 150 mb, and the chemical cloud model which places the base of the upper layer of ammonia-crystal cloud at 700 mb.

Cloud structure. The simple parcel method described above predicts the levels of cloud formation and their densities but provides no information on the horizontal distribution of cloud, which is determined largely by the air motion.

To face page 84

PLATE I—AWARDS TO CAPTAINS AND NAVIGATORS OF CIVIL AIRLINES

From left to right: Captain D. H. Mackie and Mrs Mackie, Director-General of the Meteorological Office, Mrs L. C. Williams and Navigation Officer L. C. Williams (see page 97).

PLATE II—AWARD WINNERS WITH MAJOR AND MRS K. G. GROVES

From left to right: Dr S. J. Caughey, Flight Lieutenant E. D. Peet, Mrs Groves, Major K. G. Groves, Flight Lieutenant A. N. White, Dr A. J. Gadd (see page 96).

PLATE III—MAJOR K. G. GROVES PRESENTING THE 1977 METEOROLOGY PRIZE TO DR A. J. GADD

(See page 96.)

PLATE IV—MAJOR K. G. GROVES PRESENTING THE SECOND MEMORIAL AWARD FOR 1977 TO DR S. J. CAUGHEY

(See page 97.)

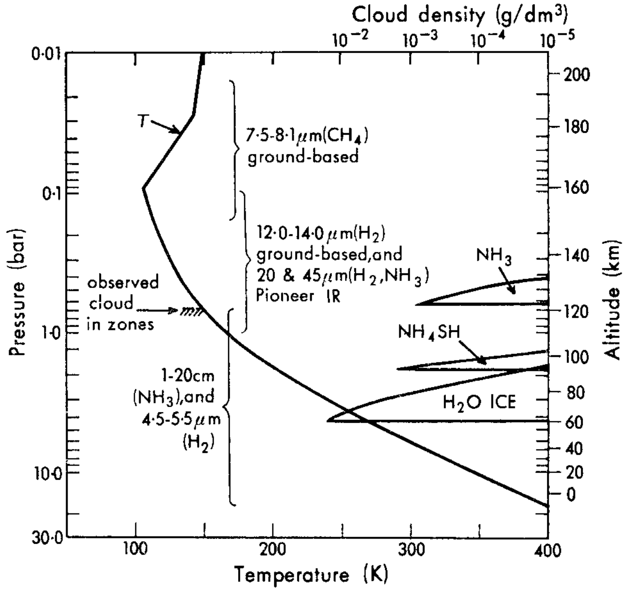

FIGURE 6—VERTICAL TEMPERATURE PROFILE OF THE JOVIAN ATMOSPHERE WITH THE POSITIONS OF THE THREE CLOUD LAYERS

Pictures from PIONEER 11, taken at its closest approach to within about 10^6 km, have a reoslution of about 200 km and confirm and extend results of ground-based studies of the horizontal arrangements of clouds in Jupiter's atmosphere and their motions. They reveal seven or eight distinct bright cloud bands (zones) running parallel to the equator and separated by darker belts. The equatorial zone is some 20 000 km wide but the zonal width decreases towards higher latitudes. The bright zones, which the infra-red radiometers show to be colder (and therefore higher) than the dark belts, are interpreted as the upper surface of the ammonia-crystal cloud layer formed as the result of ascending motions, the dark belts being regions of descent and cloud dispersal. The zones and belts are not entirely regular. Dark patches often appear in the bright zones, indicating that the ammonia-cloud cover is not always complete, and the boundaries between the zones are often serrated owing, as high-resolution pictures show, to chains of vortices 5000–10 000 km in diameter. The outstanding feature is the 'permanent' Great Red Spot in the centre of the tropical zone of the southern hemisphere (see below).

A remarkable feature of the Jovian cloud patterns is their longevity. On Earth, a particular cloud system rarely persists for more than a few days unless tied to a topographical feature; but Jupiter's surface, being fluid, has no topographical feature and yet the cloud configurations persist for at least a year. One reason may be that, because the temperatures, infra-red fluxes and emissions of the gases at cloud level are all much lower than on Earth (with radiative cooling rates of only about 10 K/year compared with about 1 K/day on Earth), the radiative relaxation time is of order 10 years, which implies that temperature anomalies are likely to take a very long time to disappear by radiative processes.

Another remarkable feature is the axisymmetric organization of the Jovian clouds along lines of latitude, which does not occur on Earth or on Venus. This may be partly due to lack of topographical features and the absence of large surface-pressure differences which cannot be supported by a fluid surface, but is mainly due to the strong control exerted by the rapidly rotating massive planet on the atmospheric circulation.

Atmospheric circulation on Jupiter. The fact that PIONEER 11 found that thermal emissions from the planet in high latitudes did not differ by more than a few per cent from those in low latitudes, despite the large excess of solar irradiation at the equator, suggests that either the atmospheric circulation is very effective in transporting heat from the equator to the poles or that the solar imbalance is largely counterbalanced by an internal heat source.

On Earth the poleward heat transfer is largely accomplished by baroclinic waves (cyclones and anticyclones) embedded in the middle-latitude westerlies, but these appear to have no counterpart in the axisymmetric Jovian circulation, which suggests that the meteorology of Jupiter is quite different from that of Earth. In the first place, the influence of the planet's rotation is much stronger on Jupiter. The rapid rotation of such a massive planet results in a mainly horizontal circulation with little vertical motion—rather like that of the deep oceans on Earth. The strong zonal flow, running parallel to lines of latitude, is almost in the Jovian equivalent of geostrophic balance. These motions are thermal winds driven by pressure differences set up by the meridional temperature gradients, their strength increasing with height at a rate proportional to the thermal gradient but, since they blow perpendicularly to the thermal gradient, they are unable to transport much heat and therefore cannot account for the observed small equator–pole contrast. However, the banded structure of the clouds suggests that the axisymmetric vortex develops instabilities with wavelength of order 10 000 km and, although these must be of a different character from that of the Earth's baroclinic waves, they may nevertheless transport heat from the relatively warm cloud-filled zones to the cooler intermediate belts and, overall, towards the poles. The most likely mechanism is shear instability leading to the development of inertial waves as a consequence of an imbalance between the centripetal and pressure-gradient forces which divide the axisymmetric vortex into a series of zonal toroidal cells corresponding to the zones and belts, as depicted in Figure 7. The circulation, involving meridional flow from zones to belts at high levels, is completed by vertical motions which release latent heat of condensation in the zones and so enhance the temperature contrasts. These temperature differences, observed to be about 3 K between zones and belts, set up pressure differences with the zones becoming regions of high pressure and anticyclonic vorticity and the belts becoming regions of low pressure and cyclonic vorticity as shown in Figure 7, and these, in turn, produce alternate bands of easterly and westerly winds. Both observations and numerical models indicate that these zonal winds tend to become concentrated in narrow jets on the boundaries of the cloud bands so that the edges of adjacent bands travel in opposite directions. The zonal winds are strongest near the equator where there is a westerly jet of about 100 m/s. The strong wind shears associated with these jets, together with the enhanced temperature gradients in the zones, may well allow the development of inertial waves of shorter wavelength, about 5000 km, than those responsible for the bands themselves and account for the rows of vortices seen on the edges of the cloud bands in the high-resolution photographs.

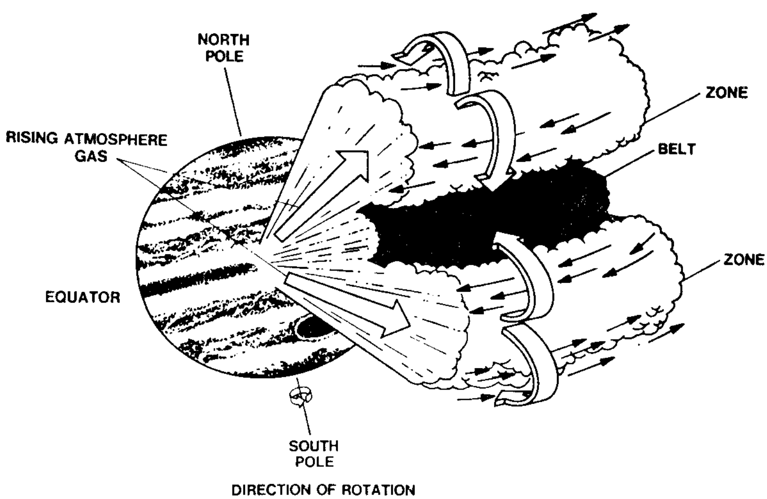

FIGURE 7—THE STRUCTURE AND CIRCULATION OF THE UPPER ATMOSPHERE OF JUPITER

The Great Red Spot. The outstanding feature of Jupiter, the Great Red Spot in the southern tropical zone, was first observed by Hooke or Cassini in 1664. An oval, stretching 25 000 km longitudinally and 12 000 km latitudinally, its area is roughly equal to that of the whole Earth's surface. Its rate of rotation about the axis of Jupiter is remarkably constant; during the last century its period has varied by only 7 seconds in nearly 10 hours. Although it has wandered in longitude over some 1200° in the last 100 years, it has varied by less than 1° in latitude during that time. It oscillates in longitude with an amplitude of about 1° and a period of about 90 days. The motions of much smaller spots in the zones and around the Great Red Spot give some information on the atmospheric motions relative to the Spot. If the movements of the small spots are not greatly affected by wave motions, they imply zonal wind speeds in the southern tropical zone of about 2 m/s relative to the Great Red Spot and circulation velocities near the spot of 20–60 m/s in the counterclockwise direction.

The mechanism responsible for the formation and maintenance of the Great Red Spot is still unknown. Hide has proposed it to be a Taylor column such as forms over a topographic obstacle in a rapidly rotating fluid. The obstacle sets up a disturbance which propagates upwards and appears at the top of the fluid as an eddy. However, since the Jovian surface is likely to have no topographic features that could anchor such a column, and it is not at all clear how such an eddy could be maintained against dissipative forces for hundreds of years, this does not seem a very likely explanation.

In a recent computer simulation of Jupiter's atmospheric circulation, Williams finds that a special type of large eddy, reminiscent of the Great Red Spot, appears between two adjacent jet streams in which smaller eddies coalesce and form a large, long-lived eddy. The absence of a solid underlying surface so reduces the energy dissipation that most features of the circulation, including the eddies, last for much longer than similar features on Earth. However, the maintenance of a large eddy for about 40 days in a model, though providing some interesting hints and insights, does not constitute a convincing explanation of the Great Red Spot, which has lasted for hundreds of years.

CONCLUDING REMARKS

The remarkable recent increase in our knowledge of planetary atmospheres, gained largely but not entirely from space probes, has allowed planetary meteorology to develop on sound lines, mainly by comparison of the results of numerical models with observations as in terrestrial meteorology.

Studies of the atmospheres of the other planets are not only of great intrinsic scientific interest in themselves but, because they exhibit such marked differences, broaden our perspectives and provide greater insight into planetary fluid dynamics as a whole and therefore a deeper understanding of the Earth's weather and climate in particular.

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FORECASTING SEA-BREEZES AT ESKMEALS

By O. W. BRITTAIN

(Meteorological Office, Bracknell)

SUMMARY

Sea-breezes at Eskmeals (54° 19′N, 03° 24′W) are complicated because of the mountainous coastal regions involved. The various types of sea-breeze are described and a diagram for forecasting them in the summer half of the year is obtained. The diagram is mainly based on (a) the difference between the screen temperature at Eskmeals (T_L) and the sea surface temperature (T_S) and (b) the free-stream wind V_f. Results of a test on the diagram carried out by forecasters at Eskmeals under operational conditions are presented.

THE TOPOGRAPHY OF THE ESKMEALS AREA

Eskmeals is situated on fairly flat sandy ground about one kilometre inland from the sea. The meteorological site is on well-drained land which lies about 8 metres above mean sea level. The coastline near Eskmeals lies roughly north to south and the joint tidal estuary of three rivers, the Irt, Mite and Esk, is about one kilometre to the north. Beyond this estuary the coastline lies south-east to north-west for about 22 km to St Bees Head (see Figures 1(a) and 1(b)). Apart from Eskdale, an enclosed valley to the north-east of Eskmeals, there is extensive high ground from 155° through east and north to 335°. Much of the mountainous surround rises to 400–600 metres but to the north-east and north-north-east a prominent cluster of peaks, including Scafell Pike, rises to nearly 1000 metres. The steep escarpment to the fells lies about 6 km to the east of Eskmeals and slightly further to the south-east. To the north-north-west, the rise to higher ground is more gradual. Apart from a range of hills 3 to 4 km distant to the north-east rising to 150–250 metres, fairly flat ground extends from the sea to the fells.

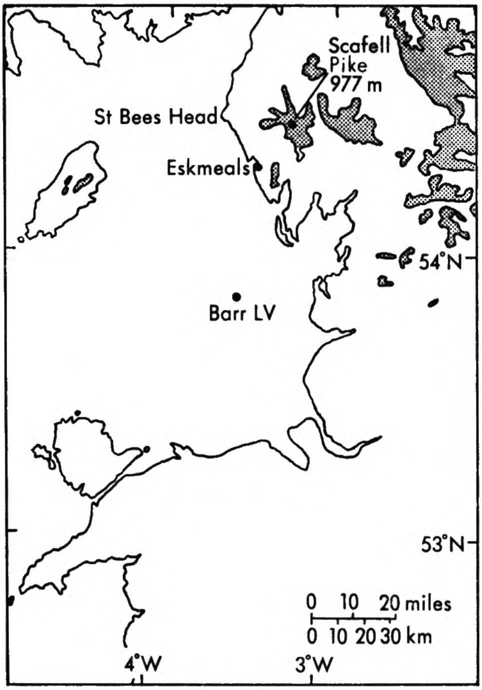

FIGURE 1(a)—THE LOCATION OF ESKMEALS
Shading indicates ground over 400 metres above mean sea level.

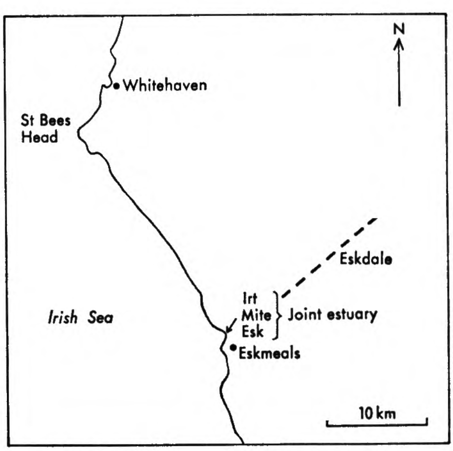

FIGURE 1(b)—MAP OF COASTAL AREA AROUND ESKMEALS

Definition of a sea-breeze at Eskmeals

A sea-breeze at Eskmeals was essentially defined as a surface wind with a direction between 190° and 310°, that is to say an onshore wind. To eliminate onshore winds which had no association with sea-breeze effects, the definition was further limited to occasions when the onshore component of the surface wind, resolved in the direction 270–090°, that is to say normal to the coastline, exceeded the onshore component of the free-stream wind resolved in a similar manner. This second restriction fails to eliminate occasions of ordinary backing of the surface wind in a northerly gradient. However, on such occasions the surface wind is north-easterly at first (a valley effect) becoming north-westerly but >310°, which does not satisfy the first restriction.

The data used

A study of sea-breezes for the period 1960–75 was made in order to distinguish between the various types which occur at Eskmeals, depending on the direction of the free-stream wind.

A method of forecasting whether or not a sea-breeze will occur was based on data for the 10 year period 1964–73. The main indicators used were (a) the difference between the air temperature at screen level over land and the sea temperature ($T_L - T_S$) which is generally accepted as being closely associated with the occurrence of a sea-breeze, which only sets in when $T_L - T_S$ is positive, and (b) the free-stream wind V_f.

Types of sea-breeze at Eskmeals

(a) During calms or light free-stream winds from any direction, the sea-breeze usually sets in from 270°. It then veers gradually at about 10 degrees an hour by 20 to 40°, in response to the Coriolis effect, followed by a prolonged spell from 290–310°. (*Note.* Anabatic and katabatic winds as well as sea-breezes and land-breezes occur in the mountainous coastal regions in which Eskmeals is situated. In particular, with clear skies and light winds, an anabatic wind sometimes sets in at Eskmeals from 210–230°, some hours after dawn. This is often before there are suitable conditions for the onset of a sea-breeze, that is to say when T_L exceeds T_S.)

(b) With measurable free-stream winds from 270° to 020° (through north) the onset of the sea-breeze is marked by a strengthening and change in direction of the surface wind which eventually becomes 290–310°. The final direction is the same as for type (a) sea-breezes but type (b) sea-breezes are usually much stronger.

(c) With free-stream winds from 020–070°, sea-breezes often occur even with strong free-stream winds. This is considered to be due to the sheltering effect of the hills on the lower layers. The direction of the surface wind usually becomes 210–230°.

(d) With free-stream winds from 070–140°, the sea-breeze usually blows from 270–310° and can occur with free-stream winds of up to 22 knots. It is possible that 'sea-breezes' associated with the stronger winds are sometimes caused by lee standing eddies set off by the hills.

(e) With free-stream winds from 140–210°, the onset of the sea-breeze is usually marked by a gradual veer and decrease in the surface wind which on many occasions eventually becomes 290–310°. During the veering process, the surface wind direction at Eskmeals often remains 210–230° for several hours.

The stronger the initial flow, the smaller the sea-breeze effect, so that on a few occasions the surface wind only veers to about 190–230°.

(f) With free-stream winds from 210–270°, the onset of the sea-breeze is occasionally marked by a small shift in surface wind direction towards west; there is usually little change in speed.

THE EFFECT OF STABILITY

From a study of upper-air soundings at Eskmeals and at stations in the main radiosonde network it was found that (1) sea-breezes will not develop until any nocturnally generated surface-based inversion has completely broken down and that (2) no particular depth of convection governs their occurrence, in contrast to experience in Lincolnshire where sea-breezes at Manby do not occur unless there is convection to 5000 ft over land (Brittain, 1966).

THE FREE-STREAM WIND (V_f) AND THE SCREEN TEMPERATURE (T_L)

The free-stream wind is usually estimated by using a geostrophic scale on surface isobars but these are difficult to draw with confidence in the Eskmeals area because of the sparse network of surface pressure observations over land and the even sparser network over the Irish Sea. Therefore on most occasions the free-stream wind was taken to be the wind speed and direction at 600 metres obtained from radar wind soundings made at Eskmeals at various times during the day, mainly between 1000 and 1530 clock time. Routine soundings made at 0715 clock time could not at first be used to obtain the 600 m wind because of the high rate of ascent, but during summer 1974 more efficient radar equipment was installed and early location of the ascending sonde was made easier. On a few occasions when radar winds were not available, V_f was estimated from surface isobars drawn on the hourly MOLFAX charts of the British Isles. For each value of V_f a synchronous value of the screen temperature at Eskmeals (T_L) was obtained.

THE SEA TEMPERATURE (T_S)

During the first year (1972) in which sea-breezes at Eskmeals were studied, values of the sea temperature reported by the Barr Light Vessel, situated almost 40 km from Eskmeals (see Figure 1) were used. During 1973, since reports from the Barr Light Vessel were no longer available, values of T_S were obtained from the 5-day mean sea temperature (MOLFAX) charts. For the earlier period 1964–71, the sea temperature for the summer half of the year was obtained from the pecked line on Figure 2 which is a curve drawn through values obtained for 1972, plotted as open circles, and for 1973, plotted as dots. For the winter half of the year the sea temperature was obtained from the solid line which was derived from an atlas of 50-year mean monthly sea surface temperatures (CPIEM, 1960).

THE FORECASTING DIAGRAM

Values of $T_L - T_S$ were plotted against the simultaneous free-stream wind speed and direction on a polar diagram, similar to that shown in Figure 3, for various times during the day when radar wind soundings were made. The symbols used indicated (1) when a sea-breeze was neither blowing at the time nor noted as having developed within the next 30 minutes, (2) when a sea-breeze which had

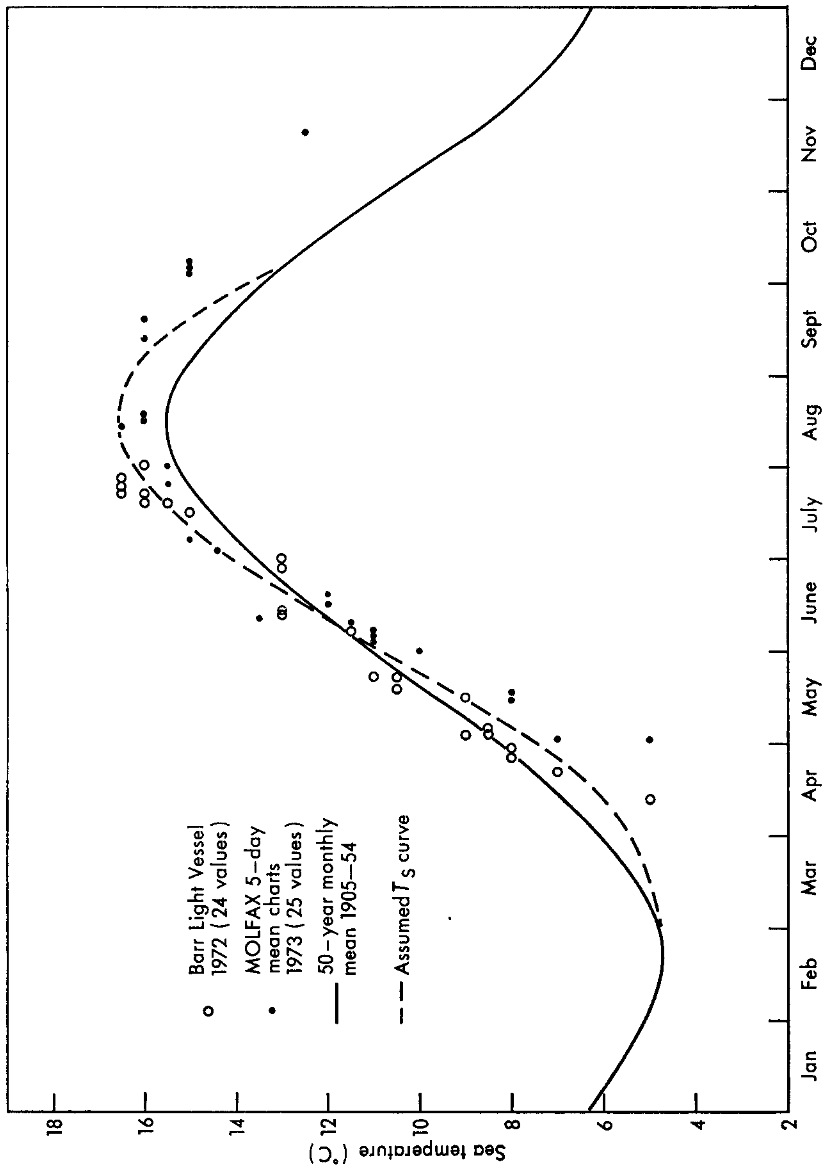

FIGURE 2—SEA TEMPERATURES IN THE ESKMEALS REGION

previously set in continued for at least 30 minutes and (3) when one subsequently developed within 30 minutes. There was a total of 654 plots of which 293 were associated with a sea-breeze and 361 were not. Figure 3 shows the resulting isopleths of $T_L - T_S$ in relation to V_f. The isopleths indicate the boundary conditions between occurrence and non-occurrence of a sea-breeze at Eskmeals, provided that there is no surface inversion of temperature. Of the 654 plots, 138 failed to fit the isopleths and the resulting contingency table is shown below.

	Sea-breeze indicated	Sea-breeze not indicated	Total
Sea-breeze occurred	207	86	293
No sea-breeze	52	309	361
Total	259	395	654

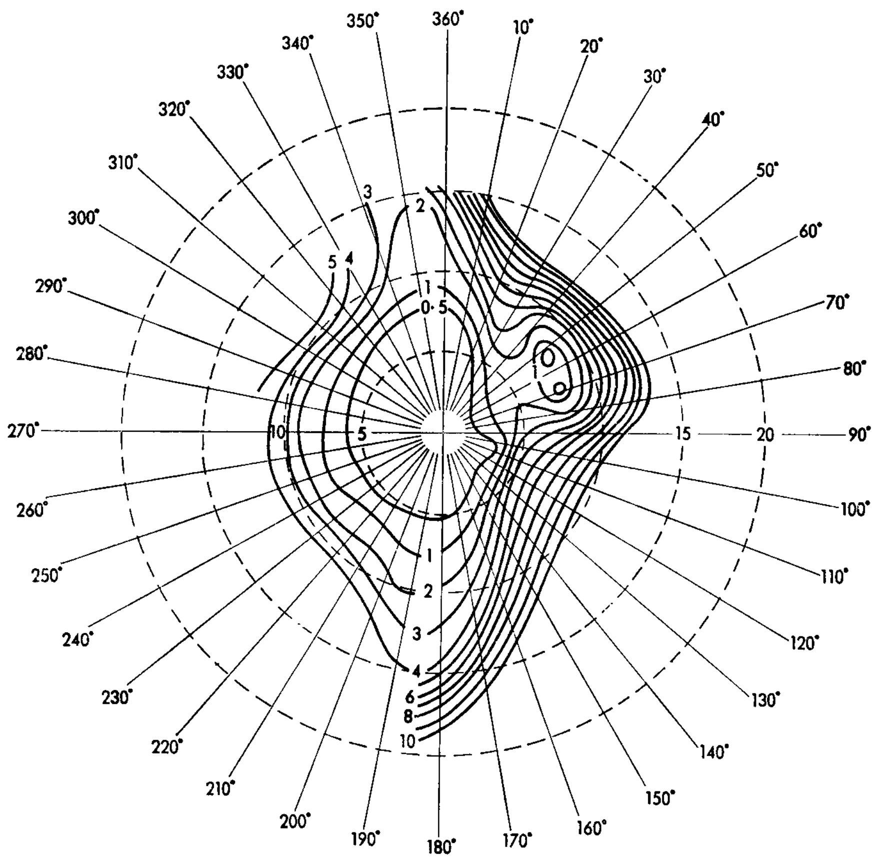

FIGURE 3—SEA-BREEZE FORECASTING DIAGRAM FOR ESKMEALS

Continuous isopleths indicate the temperature excess in degrees Celsius of the land temperature over that of the sea ($T_L - T_S$) required for a sea-breeze to develop for different values of the free-stream wind (dashed circles, speed measured in knots). Once an appropriate combination occurs a sea-breeze is likely to occur at Eskmeals within 30 minutes.

This represents a value for the Hanssen and Kuipers Index (Hanssen and Kuipers, 1965) of 0·56 and an equivalent 78 per cent success in the indication of a sea-breeze if there had been equal numbers of sea-breeze and no-sea-breeze events. However, the plots are not all independent since individual days are often associated with more than one plot. Woodcock (1976) has discussed the Hanssen and Kuipers Index in relation to other plausible measures of skill and has shown that it is superior in practical utility to χ^2 and is independent of varying trial conditions i.e. different mixtures of event and non-event days. The index is defined as follows:

Given a 2 × 2 contingency table of the form

		Forecast	
		Yes	No
Observed	Yes	a	b
	No	c	d

then

$$\text{Index} = \frac{ad - bc}{(a + b)(c + d)}.$$

AN OPERATIONAL TEST OF THE FORECASTING DIAGRAM

During the period February to October 1975, the Eskmeals forecasters used the diagram to prepare a forecast stating whether or not a sea-breeze would occur during the day. The forecast had to be completed by 0815 clock time and covered the period from 0715 or 0815 GMT to dusk. Since most sea-breezes in the summer months set in between 07 and 09 GMT at Eskmeals the routine radar wind sounding made at 0715 clock time each day was used to obtain the 600 m wind and T_L was measured at 0730 clock time. T_S was obtained from the 5-day mean sea surface temperature chart received on MOLFAX the previous day. As part of the normal forecasting processes, changes in V_f and T_L were predicted to cover the period up to dusk. The values of V_f and $T_L - T_S$ were then applied to the diagram in order to establish whether or not a sea-breeze would occur. If a sea-breeze set in before a prediction was made, no entry was made for that day. Over the whole period, 182 forecasts were made, the results of which are shown in the following contingency table:

	Sea-breeze forecast	Sea-breeze not forecast	Total
Sea-breeze occurred	52	13	65
No sea-breeze	7	110	117
Total	59	123	182

This represents a value for the Index of 0·74 and an equivalent 87 per cent success in the forecasting of a sea-breeze if there had been an equal number of sea-breeze and no-sea-breeze events. Of the 20 incorrect forecasts, it was considered that 2 were due to the failure of the diagram and 18 to errors in forecasting the indicators. For the individual months, the Index ranged from 0·32 for February to 0·87 for May which corresponds to an equivalent success rate of 66 per cent for February and 93 per cent for May.

FURTHER ASPECTS OF THE SEA-BREEZE

(a) Table I shows the number of days with a sea-breeze during each month for the years 1971 to 1975. For the years 1971 to 1974, the numbers are based on the working week, that is to say omitting week-ends, but they have been adjusted in proportion to allow for this, throwing to the nearest whole number. The numbers for 1975 refer to complete months and did not require adjustment.

TABLE I—NUMBER OF DAYS WITH A SEA-BREEZE AT ESKMEALS DURING EACH MONTH FOR THE YEARS 1971–75

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1971	4	1	7	17	17	11	25	11	13	1	1	3
1972	0	3	4	14	14	10	17	12	15	8	1	1
1973	0	6	14	11	7	17	17	12	8	0	0	0
1974	0	3	10	20	11	17	6	10	1	7	1	0
1975	0	5	6	8	17	19	15	14	3	6	0	0
Total	4	18	41	70	66	74	80	59	40	22	3	4
Per cent	0·8	3·7	8·5	14·6	13·7	15·4	16·6	12·3	8·3	4·6	0·6	0·8

Some 73 per cent of the sea-breeze days occurred in the months April–August.

(b) The time of onset of the sea-breeze was 3 to 5 hours after sunrise on 75 per cent of occasions but ranged from 2 to 10 hours after sunrise.

(c) The time of cessation was nil to 4 hours before sunset on 83 per cent of occasions but ranged from 9 hours before to 1 hour after sunset.

(d) The maximum gust during the sea-breeze occurred during the period from 1 hour before noon to 3 hours after noon on 73 per cent of occasions.

(e) The mean strength of the sea-breeze was 0·6–3·5 knots on 19 per cent of occasions; between 3·6 and 6·5 knots on 54 per cent; between 6·6 and 9·5 knots on 19 per cent; between 9·6 and 12·5 knots on 6 per cent and greater than 12·5 knots on 3 per cent.

(f) The strength of the sea-breeze did not at any time appear to be governed by the size of the term $T_L - T_S$.

CONCLUSIONS

Although sea-breezes at Eskmeals are complicated because of the high ground in the region, a sea-breeze forecasting diagram based on $T_L - T_S$ and the free-stream wind gave good results when used in practice by Eskmeals forecasters. An important consideration is that the sea-breeze will not set in until any nocturnally generated surface-based inversion has completely broken down. On the other hand, no particular depth of convection governs their occurrence, in contrast to experience in Lincolnshire. The strength of the sea-breeze does not appear to be governed by the size of the term $T_L - T_S$. Over the period 1971–75, some 73 per cent of sea-breeze days occurred in the months April–August.

ACKNOWLEDGEMENT

The author wishes to thank Mr C. L. Hawson and Mr C. A. S. Lowndes of the Special Investigations Branch of the Meteorological Office at Bracknell and his former colleagues at Eskmeals for their help, especially Mr J. H. Davies.

REFERENCES

CONSEIL PERMANENT INTERNATIONAL POUR L'EXPLORATION DE LA MER 1960 Mean monthly temperature and salinity of the surface layer of the North Sea and adjacent waters from 1905 to 1954. Service Hydrographique, Charlottenlund Slot, Denmark.

BRITTAIN, O. W. 1966 A method of forecasting sea breezes at Manby. Unpublished, copy available in Meteorological Office Library, Bracknell.

HANSSEN, A. W. AND KUIPERS, W. J. A. 1965 On the relationship between the frequency of rain and various meteorological parameters. *Meded Verhandel KNMI, De Bilt*, No. 81, pp. 2–15.

WOODCOCK, F. 1976 The evaluation of yes/no forecasts for scientific and administrative purposes. *Mon Weath Rev*, **104**, pp. 1209–1214.

AWARDS

L. G. Groves Memorial Prizes and Awards

The annual award of prizes took place on Friday 25 November 1977 at the Main Building, Ministry of Defence, Whitehall. The Air Member for Personnel, Air Chief Marshal Sir John Aiken, K.C.B., presided and the awards were presented by Major K. G. Groves. As well as Mrs Groves, several other members of Major Groves's family were present, which served to enhance the personal nature of this annual event in a most agreeable way. In view of the strike of lift maintenance workers it was perhaps fortunate that the beautifully decorated Historic Room in which the ceremony took place was no more than two floors above ground level. (See Plates II-IV.)

The 1977 Aircraft Safety Prize was awarded to Flight Lieutenant A. N. White of Royal Air Force Scampton with the following citation:

'Flight Lieutenant White's "Vulcan Miscellany" presents to all Vulcan aircrew, in an easily readable style, a unique and permanent collection of the significant accidents, incidents and handling aspects which have occurred over the years. As a result Vulcan crews are aware of the many problems encountered in the past and how they were handled. With this valuable knowledge they can prepare their own reactions to potential emergencies with confidence. It also shows how current operating procedures and orders have been developed and what can happen in certain circumstances if they are ignored; apart from re-emphasizing their validity, it also provokes thought on their future development. The miscellany is also an idea capable of further development beyond the flight safety aspects of systems operations into the field of operational training.

It is in recognition of his initiative and practical contribution to the safety of Vulcan aircrew and the possibility of the idea being applied to other aircraft that Flight Lieutenant White has been awarded the 1977 L. G. Groves Aircraft Safety Prize.'

The 1977 Meteorology Prize was awarded to Dr A. J. Gadd of the Meteorological Office with the following citation:

'For the past ten years Dr Gadd has been engaged in the development of numerical forecasting models and of their practical applications. He has been responsible for the incorporation of many significant improvements into operational routines especially in the fields of initialization, time integration and output. His work on the split explicit time integration scheme recently incorporated into the main operational model has led to substantial savings of computer time and greater flexibility in the numerical forecasting system.

Dr Gadd has been concerned with refinements in the modelling of temperature and wind and with adaptations of computer output which have had direct application in the provision of meteorological services for aviation. These include the output of forecast data in grid point form for use in computers used by airlines and air traffic control authorities in flight planning and in the direction of aircraft operations. In his contacts with members of the aviation industry Dr Gadd's evident authority, depth of expertise and co-operative approach have invariably led to the appreciation of the users and to confidence in the solutions found to their problems.'

The 1977 Meteorological Observer's Award was awarded to Flight Lieutenant E. D. Peet of the Meteorological Research Flight, RAE Farnborough with the following citation:

'Flight Lieutenant Peet has served with the Meteorological Research Flight as a pilot for the last four years and has identified himself to an unusual degree with the scientific tasks of the Flight. This has enabled him to make a positive and worthwhile contribution to the planning of the flights and to the development of both the Hercules and Canberra aircraft as tools for research. During actual flying operations his keen interest, relevant comments and general helpfulness have done much to ensure that each flight has been conducted in such a way as to make maximum use of its opportunities for the scientific study of weather phenomena.'

The 1977 Second Memorial Award was awarded to Dr S. J. Caughey of the Meteorological Research Unit at Cardington with the following citation:

'For the past three years Dr Caughey has been the leader of the team at Cardington engaged on the experimental and theoretical study of the boundary layer. He has made many contributions to the analysis and interpretation of data from major field experiments, helping to present a more ordered picture of the complex processes at work in the lower atmosphere.

He has been quick to develop and exploit the potential of new methods of observation, in particular the use of sound pulses to study the small-scale pattern of wind and temperature fluctuations. The careful experiments of the Cardington team have established a firm quantitative foundation for this technique and pointed the way to important practical applications in measuring such things as wind shear and fog-top height.'

Meteorological Office awards to captains and navigators of civil airlines

Since 1954 the Director-General of the Meteorological Office has made awards annually to encourage in-flight and post-flight weather reporting by captains and navigators on the staff of civil airlines. The awards have been of two kinds: books, suitably inscribed, have been awarded to captains and navigators who have provided the best series of reports during the year under review, and captains (and exceptionally navigators) who have given long and meritorious service in the provision of air reports have been given brief-cases.

For a number of reasons including the trend towards self-briefing, remote briefing facilities at air terminals, and the introduction of the practice of designating aircraft to provide AIREPs on Atlantic routes, it has become increasingly difficult to maintain a workable and fair system of marking as a basis for the awards. In the circumstances it has been decided that the system should be wound up and that the awards for 1976 will be the last. Since the scheme began there have been 46 awards of brief-cases and 439 book awards.

The final presentation of brief-cases took place at the Meteorological Office College, Shinfield Park, near Reading on 25 October 1977 when the Director-General presented the awards to Captain D. H. Mackie, formerly of British Airways, and to Navigation Officer L. C. Williams, formerly of British Caledonian Airways. This was only the second occasion on which a brief-case had been awarded to a navigator. (See Plate I.)

REVIEW

Meteorology for glider pilots, third international edition, by C. E. Wallington, 240 mm × 140 mm, pp. xi + 331, *illus.* London, John Murray, 1977. Price: £8.50.

The first edition of this book was published in 1961. It was the outcome of a decade which had seen much fruitful interplay between meteorologists and pilots in the developing sport of cross-country gliding. The book was firmly based on the author's own experience in the air, as well as on his theoretical knowledge and meteorological instinct. Written in a style that was at once personal yet authoritative it became, and has remained, the popular standard work on meteorology for the gliding movement in this country.

For this new edition there has been a major reshaping of the original text. It is still recognizably the old 'Wallington' though there have been many changes in text, diagrams and plates. The description 'international' is justified by the inclusion of many southern-hemisphere weather maps and other material drawn from the author's recent experience in Australia, where he now lives, and elsewhere.

The book is now arranged in four distinct parts of which the first is entitled 'General meteorology'. This is a basic course on the elements of meteorology addressed to amateur pilots. It differs little from many other such courses, though it includes a chapter on tropical weather which is new to this edition.

The second part entitled 'Gliding meteorology' will be the kernel of the book for most meteorologists. It has chapters on Airflow over hills; Dry thermals; Cumulus convection; Convective storms; Sea-breezes; and Lee waves. All these topics were covered in the first edition and much of the original text is still intact, since most of the nuts and bolts of gliding weather were well understood by 1961. It is interesting to consider how far we have advanced since then, especially in our knowledge of the variability of convective phenomena on the 'meso' scale. In this country at least it has seemed that the gradual improvement in the performance of gliders over the past sixteen years has been accompanied by a corresponding decrease in the meteorological feedback.

From his international vantage point Wallington has been able to shed a little new light, but in general it is clear that the advances of recent years have been small. However, the new sections describing the simultaneous occurrence of thermals and lee waves are a very welcome corrective to older ideas that these two phenomena were mutually exclusive. Other new material includes a note on the cellular organization of thermals over flat terrain in Australia, and a description of some interesting orographic convergence effects in the USA. Although the chapters on 'Convective storms' and 'Sea-breezes' have little that is essentially new, the latter does contain some recent case studies which are a welcome change from the generalized descriptions that form the bulk of the text.

The final two parts are quite short. 'Weather forecasts' gives practical advice to pilots on obtaining forecasts from a national meteorological service that are tailored to the needs of gliding. 'Technical notes' is a short appendix where such subjects as geostrophic winds and tephigrams can be kept at a safe distance from those readers who like 'weather' but are allergic to 'meteorology'.

The book has been written for glider pilots, and its reshaping has been done to make it more attractive to that audience. From his different standpoint, the meteorologist can applaud the new layout, but he will regret that there has been some decrease in scientific content, deliberate though this may have been. Those who knew the older editions will find that beyond the rearrangement and expansion of the text, this edition has rather little to report that is substantially new. But to those who have never yet delved into 'Wallington' there can be no hesitation in recommending it as an excellent exposition, in popular but authoritative style.

P. G. WICKHAM

551.524.36(41-4)

LETTER TO THE EDITOR

The exceptional heat-wave of 23 June to 8 July 1976

Mr Shaw's interesting article, in the October 1977 *Meteorological Magazine*, on the hot spell of 23 June to 8 July, is just a bit misleading in the matter of low humidities. While it was indeed unusual for relative humidities of less than 20 per cent to occur as they did, e.g. on 30 June 1976, over a wide stretch of lowland England, Mr Shaw seems to go a bit astray when he considers these occurrences in the context of previous occasions. It is doubtful if a value of 4 per cent relative humidity has, this century, occurred only in March 1965, and in that month it was recorded at other places than Manchester Airport and Great Dun Fell; indeed it seems to have got down to 2 per cent at Strachan in Kincardineshire (Green, 1966). But the records of Ben Nevis Observatory show that very low relative humidities were (and undoubtedly still are) not so very rare on that summit; with the help of some of the staff of the Meteorological Office, I documented two cases (Green, 1967) where the relative humidity was apparently zero.

Inspection of the daily aerological records shows that occasions when there is dry air not far above the surface are fairly common, but the boundary layer usually insulates them from the surface, except on hill-tops. The dryness is, not surprisingly, usually greatest in winter anticyclones, and the Ben Nevis records show that occurrences of low relative humidity at the Observatory were commonest in winter. There was a secondary maximum in May–June, and this is the period when low relative humidities are commonest in the lowlands; diurnal heating, in warm anticyclonic conditions in early summer, easily transforms *rather* low relative humidity, during the day, to *very* low relative humidity.

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REFERENCES

GREEN, F. H. W. 1966 Low air humidities, 28 March to 2 April 1965. *Weather*, **21**, pp. 101–104.

1967 Air humidity on Ben Nevis. *Weather*, **22**, pp. 174–184.

SHAW, M. S. 1977 The exceptional heat-wave of 23 June to 8 July 1976. *Met Mag*, **106**, pp. 329–346.

Mr Shaw has commented on the above letter as follows:

'The section on low humidities was intended as an item of extra interest and was in no way as exhaustively researched as the sections on temperature records. I should be surprised if serious objections to the latter were raised, but it does not surprise me at all that someone who has himself written articles specifically on cases of very low relative humidity should be able to raise critical comment. My phrase 'believed to be the lowest recorded this century' was taken, as far as I remember, from one of the references quoted and in retrospect, I suppose, it invited comment such as that of Mr Green.

'My main comparison was with the list given in the *Climatological Atlas* covering a 22 year period and I assumed that such a list *had* been fairly well researched. The '4%' item was thrown in as an extra, perhaps rashly. Mr Green's last sentence surprises me a little. I did not know of the tendencies to low humidities in May–June but if 'rather' low R.H. was easily transformed into 'very' low R.H. there would surely be many more instances recorded at our low-level stations. It would seem from my brief look at the subject that while R.H. of the order of 25–30% may not be uncommon in hot weather, values below 20% are rare at low levels.'

EDITOR

THE METEOROLOGICAL MAGAZINE

NO. 1268 MARCH 1978 VOL. 107

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1 monthly **Annual subscription £13.14 including postage**

Dd. 497684 K15 3/78

ISBN 0 11 724797 9
ISSN 0026-1149

Met.O.915

METEOROLOGICAL OFFICE

the meteorological magazine

APRIL 1978 No 1269 Vol 107
Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.915

THE METEOROLOGICAL MAGAZINE

No. 1269, April 1978, Vol. 107

RETIREMENT OF DR R. J. MURGATROYD, O.B.E.

Dr R. J. Murgatroyd, O.B.E., Deputy Chief Scientific Officer in the Dynamical Climatology Branch of the Meteorological Office, retired from the Office on 16 February 1978. His early career was at the Rugby Radio Station of the General Post Office. While there he studied for and obtained a B.Sc. degree in Electrical Engineering. He transferred to the Patent Office as an Assistant Examiner in 1938 but shortly before the outbreak of war he joined the Royal Air Force Volunteer Reserve and was posted to the Meteorological Office Training School as a Pilot Officer. He served as a forecaster at several RAF stations and rose to the rank of Flight Lieutenant but his most significant war-time postings were to Larkhill for a course in sound ranging and later to various Army units where he was given the job of measuring winds at high altitudes by observing the movement of smoke from shells fired to a height of 30 km by a special 'hyper-velocity' gun and also by the less direct method of observing sound waves from distant ground explosions. This work was the start of the long and detailed studies which have given Dr Murgatroyd a unique knowledge of, and world-wide authority in, the affairs of the upper atmosphere.

His formal transfer to the Meteorological Office as a Senior Scientific Officer in 1946 was followed by postings to Larkhill and then, for three years, to Germany. In 1951, on promotion to Principal Scientific Officer, he took charge of the Meteorological Research Flight (MRF) at Farnborough and saw it through a time of rapid development when new aircraft—the Hastings, Canberra and Varsity—were coming into service and new instruments to exploit their capabilities were being developed. Dr Murgatroyd's varied background made him an ideal leader over the whole spectrum of MRF activities, but he also found time to extend his own studies of the atmosphere far above aircraft heights. By the systematic use of meteorological theory he was able to weld together diverse but scanty experimental data—from balloons, a few rockets, sound propagation, high-level clouds, meteor trails and so on—to produce by 1957 a coherent picture of the distribution of winds and temperatures up to 100 km which has been remarkably little changed by the vastly greater numbers of observations which have accumulated since. This work led to the award of a Ph.D. degree and the L. G. Groves Memorial Prize for Meteorology in 1958.

In 1957 Dr Murgatroyd was promoted to Senior Principal Scientific Officer in the new post of Chief Meteorological Officer, MRF and then in 1962 the value of his research was recognized by his transfer to Special Merit status in the General Circulation Branch, which freed him from administrative duties. The quality of his work at MRF, which had already brought him the Darton Prize of the Royal Meteorological Society in 1956, was honoured by the award of an O.B.E. in 1963. He was not left to pursue his research undisturbed for as his reputation grew there were increasing demands on him as a lecturer, as a member of committees of the World Meteorological Organization, the International Association of Meteorology and Atmospheric Physics and other organizations and as Editor of the *Quarterly Journal of the Royal Meteorological Society*. In 1971 he gained the rare Special Merit promotion to Deputy Chief Scientific Officer and a year later he was appointed Chairman of the Committee on Meteorological Effects of Stratospheric Aircraft (COMESA). This committee was set up to direct a widespread and urgently pursued program to assess the effects of aircraft operations (in particular, Concorde) on the composition and meteorology of the atmosphere. Under Dr Murgatroyd's leadership COMESA brought together work from the universities, government departments and industry that covered all facets of the problem and produced a report of unassailable authority which proved an effective counter to earlier alarming predictions based on inadequate or improperly understood evidence. This work, for which he received the L. G. Groves Prize again in 1975, has proved a fruitful starting point for further studies of the stratosphere, studies which are fortunately not likely to end with Dr Murgatroyd's formal retirement.

These bare facts of an impressive career give little idea of the influence that Dr Murgatroyd has always exerted on those round him. His example of hard and thorough work, looking at every aspect of a problem, but with a sound scientific instinct for those aspects likely to be important, has been all the more effective for the quietness and complete lack of ostentation with which he has carried his considerable reputation and authority. We have all admired his combination of high scientific achievement and unselfish co-operativeness; he has been one of those who set the standards on which the life and work of the Office rest. We wish him and his wife an active and happy retirement.

K. H. STEWART

551.501.796:551.575.1.

ACOUSTIC SOUNDING OF RADIATION FOG

By S. J. CAUGHEY, W. M. DARE and B. A. CREASE
(Meteorological Research Unit, RAF Cardington, Bedfordshire)

SUMMARY

Acoustic sounder echo patterns typical of those obtained at Cardington during instances of radiation fog are described and discussed. The height of a strong elevated layer echo is shown to be closely correlated with the fog depth. Acoustic estimates of the fog depth are compared with those from the traditional (profile) method and the potential usefulness of this technique for monitoring radiation fog evolution is illustrated by a case study.

1. INTRODUCTION

An important parameter in the forecasting schemes currently used for the prediction of radiation fog clearance is the fog depth, D. The estimated fog clearance temperature, T_2, and dawn temperature, T_1, along with the fog depth enable an estimate to be made of the time required (following dawn) for the fog to clear (Barthram, 1964). The fog depth is usually assessed by inspection of Cardington Balthum temperature and humidity profiles through the fog (Painter, 1970), or, though with much less accuracy, by the use of a representative radiosonde ascent. The potential temperature profiles usually reveal the existence of a strong inversion associated with the fog top. This is formed by the lifting of the nocturnal inversion following fog formation and the continued radiational cooling from the fog top. Above the radiatively shielded ground a superadiabatic lapse rate develops and helps to establish a convective regime within the fog in which soil heat flux is transferred upwards (Roach *et alii*, 1976).

One technique used to determine the height of the fog top at dawn uses information from the midnight Balthum ascent. From the profiles of temperature and dew-point plotted on a tephigram the nose of the temperature inversion is raised by 5 mb and the temperature decreased by 1·5 K; this point is then joined to the night minimum temperature by a straight line. The intersection of this line and the dew-point curve provides an estimate of the fog depth at dawn (Heffer, 1965). Clearly this method relies upon conditions being well behaved between the time of the ascent and dawn. Furthermore the accuracy of any prediction deduced from a single ascent depends on the spatial representativeness of the ascent itself. Aircraft and tower observations indicate that the fog top is often perturbed by low frequency waves propagating in the stable air aloft with the result that the surface of the fog takes on a somewhat 'corrugated' appearance. Obviously the information obtained about the fog top depends upon the point of traverse through this surface. It is the purpose of this paper to demonstrate that a monostatic acoustic sounder may be usefully employed in the study of radiation fog and also provides an alternative method capable of continually monitoring the fog depth.

The propagation of sound in the atmosphere has been a topic of research for at least one hundred years (see Tyndall, 1874). In 1946 Gilman, Coxhead and Willes of the Bell Telephone Laboratories reported the detection of acoustic echoes of unexpectedly high intensity, much greater than could be accounted for by reflection alone. However, many years elapsed before it was shown by McAllister (1968) that these echoes could be easily obtained and displayed (for ease of appraisal) in height/time form on a facsimile chart recorder. He also provided some evidence that the echoes were generated by the scattering of sound from inhomogeneities in the temperature field on a scale of about half the wavelength of the transmitted sound.

2. Theoretical background

The theory of the scatter of sound by turbulent velocity fluctuations in the atmosphere or by fluctuations in scalar atmospheric variables such as temperature and humidity has been investigated by several authors, for example Lighthill (1953), Kraichnan (1953), Kallistratova (1959) and Monin (1962). Following Monin, the scatter of sound in dry air by inhomogeneities can be expressed, assuming a Kolmogorov spectrum of turbulence, by

$$\sigma_T(\theta) = 0{\cdot}03\ k^{1/3} \cos^2 \theta \left[\frac{C_V^2}{C^2} \cos^2(\tfrac{1}{2}\theta) + 0{\cdot}13 \frac{C_T^2}{T^2} \right] (\sin \tfrac{1}{2}\theta)^{-11/3} \qquad .. \quad (1)$$

where $\sigma_T(\theta)$ is the scattered power per unit volume, per unit incident flux, per unit solid angle at a direction θ from the initial propagation direction; k is the wave number of the acoustic transmitted wave; C and T are the mean velocity of sound and mean temperature in the scattering volume respectively; C_V^2, C_T^2 are the structure parameters for the wind and temperature fields, defined by the expressions

$$C_V^2 = \overline{[V(x) - V(x + r)]^2}/r^{2/3}$$

$$C_T^2 = \overline{[T(x) - T(x + r)]^2}/r^{2/3} \qquad .. \quad .. \quad .. \quad .. \quad .. \quad .. \quad (2)$$

where $V(x)$ is the instantaneous wind speed at a point x in the direction x to $x + r$, $T(x)$ is the instantaneous temperature at point x, and $V(x + r)$ and $T(x + r)$ are the corresponding instantaneous values at point $x + r$. For backscattered sound (i.e. a monostatic sounder configuration with co-located transmitter and receiver) $\theta = 180°$ so reducing equation (1) to

$$\sigma_T(180) = 0{\cdot}008 \frac{C_T^2}{T^2} \lambda^{-1/3}, \qquad .. \quad .. \quad .. \quad .. \quad .. \quad .. \quad (3)$$

thereby implying that the echo strength is determined, in this case, by the temperature structure parameter C_T^2 while also being weakly dependent on the wavelength of the transmitted sound, λ. Equation (3) has been shown to be a fairly good approximation by recent experimental work; see for example Asimakopoulos *et alii*, 1975 and 1976; Neff, 1975; and Haugen *et alii*, 1975. The results have indicated that the intensity of the backscattered sound may be used to obtain a reasonable estimate of C_T^2. Caughey *et alii* (1978) have also shown that in convective conditions satisfactory estimates of C_V^2 can be obtained from bistatic acoustic sounder returns by using equation (1). The theory outlined above ignores the contributions to the scattered sound from humidity fluctuations and the reflection of sound from sharp gradients of refractive index. However, it appears that in many cases these terms are typically one or two orders of magnitude lower than the temperature and velocity contributions and can therefore be ignored (Little, 1969). In fog the possibility exists of an additional contribution to the echo intensity due to Rayleigh scattering from the fog water droplets. Using an approximate form of Rayleigh's (1872) theory for the scatter of sound by a spherical particle whose diameter (d) is much smaller than the acoustic wavelength (λ) (a good approximation for fog since $d/\lambda \approx 10^{-5}$), Little (1972) has shown that the scattering cross-section per unit volume is

$$\sigma_D(\theta) = \frac{\pi^5}{9\lambda^4}\,[1 - \frac{3}{2}\cos\theta]^2\left(\frac{1}{V}\sum_V d^6\right), \quad \ldots \quad (4)$$

and hence for backscattered sound

$$\sigma_D(180) = \frac{25\pi^5}{36\lambda^4}\left(\frac{1}{V}\sum_V d^6\right). \quad \ldots \quad (5)$$

For the scatter from fog droplets to be detectable it must exceed the noise limit of the system. This is determined principally by the local environmental noise level (i.e. wind noise, traffic noise, etc.) rather than the limiting thermal noise from the random motion of atmospheric molecules or the electron shot noise in the receiver electronics. The quantitative comparisons at Cardington between acoustic echo intensities and the direct measurement of $C_T{}^2$ have shown that this environmental noise generally limits the smallest $C_T{}^2$ values measurable to something greater than 10^{-6} K^2 m$^{-2/3}$. From equation (3), then, the minimum scattering coefficient detectable with the present Cardington sounder is of the order of 10^{-13} m^{-1}. Measurements available of fog droplet spectra (Brown, private communication) permit an estimate of the typical scattering cross-section $\sigma_D(180)$ to be expected from radiation fogs. The value obtained of 10^{-15} m^{-1} is two orders of magnitude smaller than the minimum detectable and hence it would seem that the echoes recorded by the Cardington monostatic sounder in fog conditions are generated principally by small-scale temperature inhomogeneities. It is worth noting, however, that for scattering through ninety degrees $\sigma_T(90)$ is zero whereas $\sigma_D(90)$ is still appreciable and thus the possibility remains that an acoustic system could be constructed which would monitor only the presence of water droplets or other hydrometeors.

3. Experimental details

The Cardington Acoustic Sounder has been described in a previous article (Crease *et alii*, 1977) so only a brief outline is given here. The acoustic array consists of a 6 × 6 arrangement of small, re-entrant horn loudspeakers separated by the half wavelength of the transmitted sound, which, with an operating frequency in the range 1·5–2·0 kHz, is about 0·1 m. Short-duration (about 30 ms), high-intensity bursts of sound are directed vertically into the atmosphere at fixed intervals of typically 2·0 seconds. After loudspeaker ringing has ceased, the array is switched to the listening mode and any echoes received are amplified (by a factor of up to 10^7) and displayed on a facsimile recorder.

During the 1976/77 winter the acoustic sounder was put into operation whenever conditions appeared favourable for the formation of radiation fog. In addition Balthum ascents were made at regular two-hourly intervals to obtain profiles of wind speed, temperature, humidity and pressure across the depth of interest. Echo patterns typical of those obtained in radiation fog show a strong layer echo overlying a region usually exhibiting evidence of convective activity (Crease *et alii*, 1977). This supports evidence from direct measurements of turbulent mixing within fogs (Roach *et alii*, 1976). The layer echo is considered to be generated by the interaction of convective plumes with the sharp temperature gradients associated with the fog top and by temperature fluctuations resulting from breaking wave activity. Clearly radiative cooling and the region of temperature inversion will extend some distance into the fog and so the exact relationship between the position of the layer echo and the fog top is difficult to specify.

4. Comparison of sounder and profile estimates of fog depth

Over the period October 1976 to February 1977 a total of four cases of radiation fog were studied. The fog depth was taken as the lower bound of the layer echo in the sounder returns. From the profiles of temperature and humidity the highest level with zero wet-bulb depression and the first level to indicate significant temperature increase and wet-bulb depression were averaged for an estimate of the fog top. This latter method introduces a tolerance dependent on the vertical resolution of the Balthum profile. In the present case this implies an error of about ± 60 m on the fog depth estimate. The tolerance on the sounder estimate depends upon the width of the acoustic pulse, which will act to broaden a narrow region of intense thermal activity, as well as the oscillations in the height of the layer echo which occur on time scales varying from a few minutes to several hours. The comparison of fog depth estimates for all available occasions is given in Figure 1, the typical tolerances on the estimates being denoted by the error bars. Generally good agreement is indicated for fog depths between 60 metres and 240 metres. On one occasion when a droplet spectrometer was available the actual height of the fog top was monitored over a three hour period on the early morning of 27 October 1976. The results (see Figure 2) demonstrate a clear correlation between the height of the layer echo and that of the actual fog top.

5. Case study of radiation fog on 14/15 November 1976

To illustrate the potential of acoustic sounding in monitoring the evolution of radiation fog a description is given of the sequence of events which occurred between fog formation and dissipation on 14/15 November 1976.

(a) *Synoptic situation*

On 14 November 1976 a ridge of high pressure extended south-westwards across south-east England from an anticyclone centred over Scandinavia. In the East Midlands and East Anglia fog which had formed in the early morning persisted throughout the day in many districts, whereas in the Cardington area it had cleared by midday. With light winds, moist air and nocturnal cooling conditions were conducive to the reformation of radiation fog. By 1550 GMT ground fog had formed and this then began to deepen and thicken. During the night a weak frontal system moved into south-west England and Wales and associated patches of stratocumulus cloud were evident in the south Bedfordshire area from about midnight onwards.

(b) *Relationship between acoustic sounder facsimile records, wind and temperature profiles and surface net radiation*

The sequence of low-level wind speed and temperature profiles during the early period of fog formation is shown in Figure 3. As the fog began to deepen after

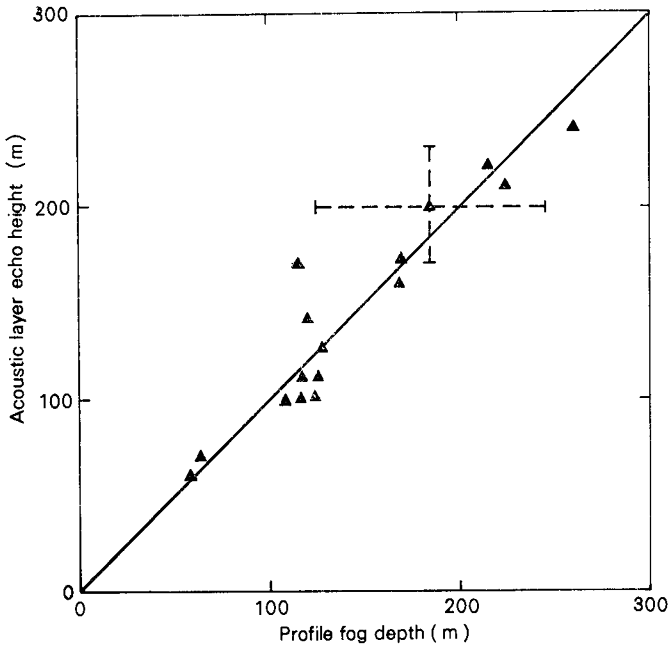

FIGURE 1—COMPARISON OF ACOUSTIC SOUNDER LAYER ECHO-HEIGHT AND ESTIMATES OF FOG DEPTH FROM TEMPERATURE AND HUMIDITY PROFILES

1800 GMT the surface-based radiation inversion started to dissipate owing to the gradual decrease in long-wave radiational cooling and the soil heat flux acting to raise the surface temperature. During this period the 0·5 m temperature rose by ≈2 °C whereas at 16 m the temperature fell. Mean winds up to 8 m height remained in the range $\frac{1}{2}-1\frac{1}{2}$ m s^{-1}. The sharply rising echo layer on the acoustic facsimile chart (Figure 4) evident at around 1830 GMT is most probably associated with the fog top and it is clear that when the fog depth exceeded about 100 m the Richardson number in the surface layer had fallen to ≈0·1 (eventually becoming negative around 2200 GMT) and the net radiation increased to near zero.

Shown in Figure 5 is the sequence of Balthum soundings obtained on this night. The early evening profiles show the presence of a strong nocturnal inversion extending up to about 30 m. By 2038 GMT, however, with the formation and deepening of the fog, the profiles had altered significantly and indicated the presence of a fairly deep saturated adiabatic layer. On the next ascent (2310 GMT) the depth of this layer is maintained but in subsequent profiles some decrease is apparent so that by 0626 GMT a surface-based inversion was again in evidence and the fog had dispersed.

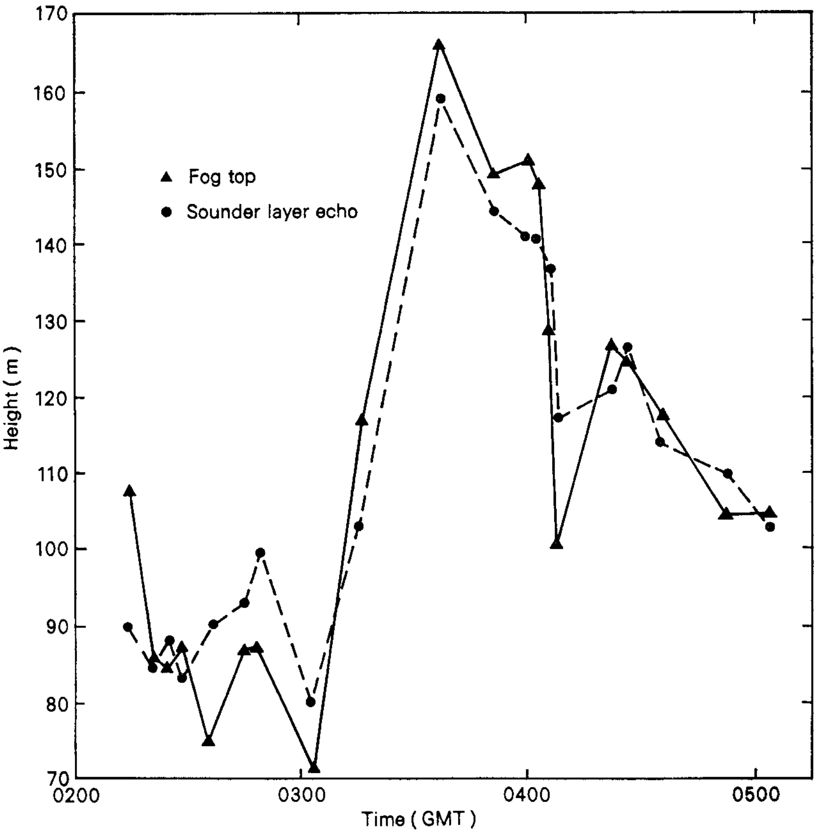

FIGURE 2—COMPARISON OF ACOUSTIC SOUNDER LAYER ECHO-HEIGHT (●) AND MEASUREMENTS OF THE FOG TOP HEIGHT (▲), OBTAINED BY USING A BALLOON-BORNE DROPLET SPECTROMETER, BETWEEN 0200 AND 0500 GMT ON 27 OCTOBER 1976

These implied variations in the fog depth correlate well with the movement of the layer echo height on the sounder facsimile chart (see Figures 4 and 6). This shows a gradually deepening fog up to about 2100 GMT after which time a slow and erratic decrease begins with the layer echo becoming generally more tenuous and broken. A gradual improvement in visibility began at around 0500 GMT reaching 500 m by 0600 GMT and 1000 m shortly afterwards, when a nearly complete layer of stratocumulus cloud at around 1700 m was apparent. Consistently with these developments the acoustic layer echo became progressively weaker and more diffuse, gradually merging with other echoes as the general echo pattern returned to one more typical of a stable boundary layer.

6. CONCLUDING REMARKS

This paper has demonstrated that an acoustic sounder may be usefully employed in the study of radiation fog and in particular enables reasonably accurate

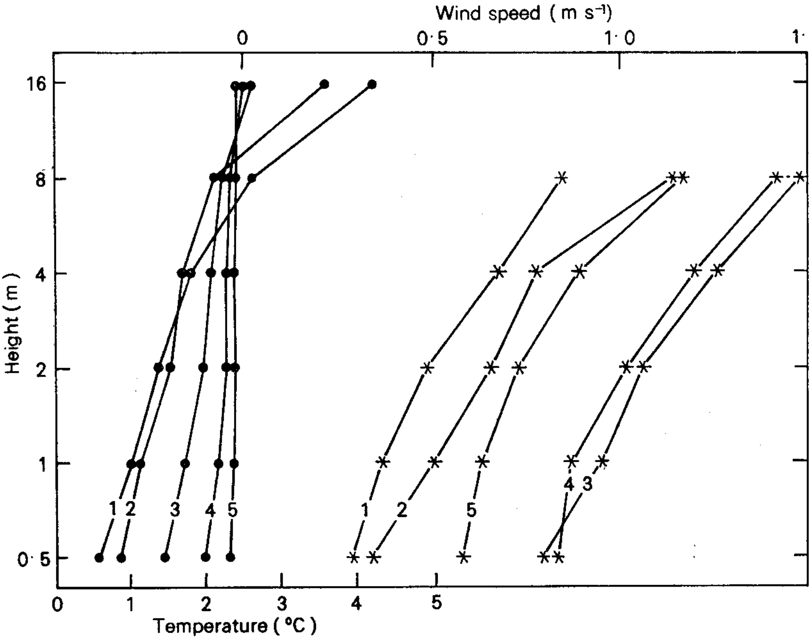

FIGURE 3—PROFILES OF WIND SPEED (*) AND TEMPERATURE (●) DURING THE INITIAL PERIOD OF FOG FORMATION ON 14 NOVEMBER 1976

The profiles are consecutive ten minute averages over the period 1750 to 1840 GMT.

estimates of the depths of established fogs to be made. Additionally since the sounder can be used continually it provides valuable information on the evolution of the fog and in the period following dawn the weakening of the layer echo can be monitored and the progress towards fog clearance observed. A detailed investigation of the microphysics at the fog top is required in order to elucidate the relationship between the acoustic layer echo, the temperature profile, the turbulence field and the actual fog top.

ACKNOWLEDGEMENTS

The authors wish to thank their colleagues at the Meteorological Research Unit, Cardington for assistance in all stages of this work. Thanks are also due to Dr W. T. Roach and Mr R. Brown for providing information on the fog droplet spectra and the variation in the fog-top height with time included in Figure 2.

REFERENCES

ASIMAKOPOULOS, D. N., COLE, R. S., CAUGHEY, S. J. and CREASE, B.A. 1976 A quantitative comparison between acoustic sounder returns and the direct measurement of atmospheric temperature fluctuations. *Boundary Layer Meteorology*, **10**, pp. 137–147.

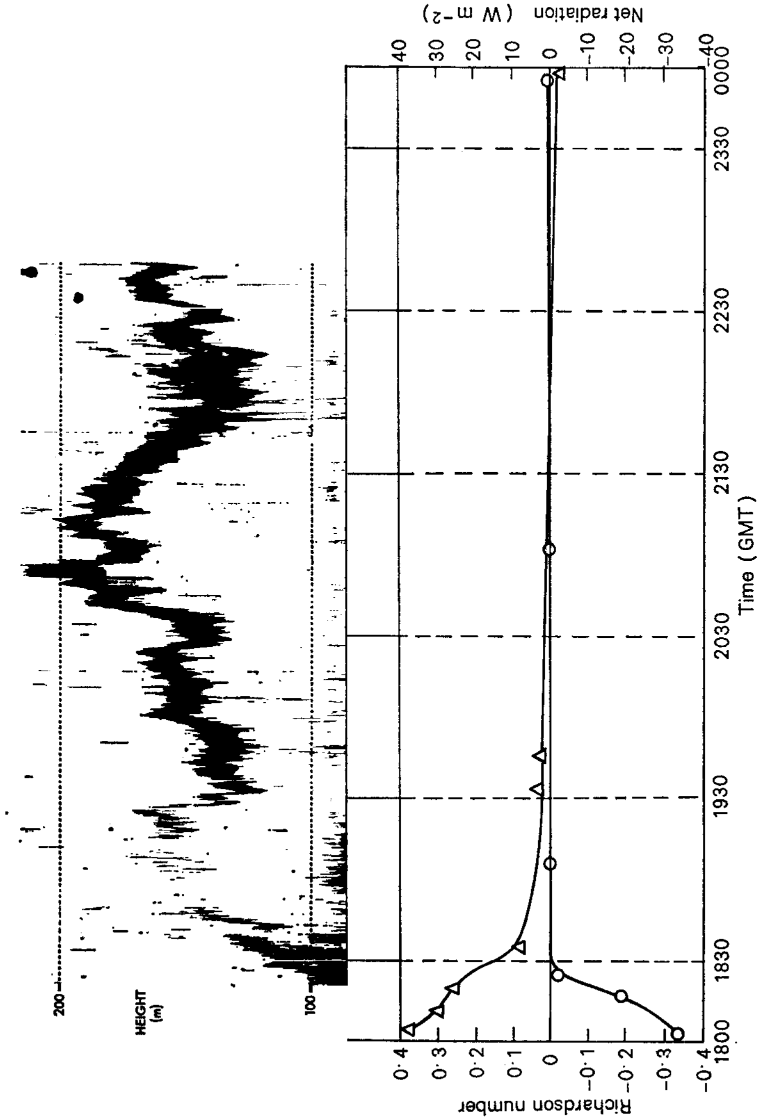

FIGURE 4—VARIATION OF ACOUSTIC SOUNDER LAYER ECHO-HEIGHT WITH TIME ON 14 NOVEMBER 1976 AND COMPARISON WITH SURFACE LAYER RICHARDSON NUMBER (Δ) AND NET RADIATION (○)

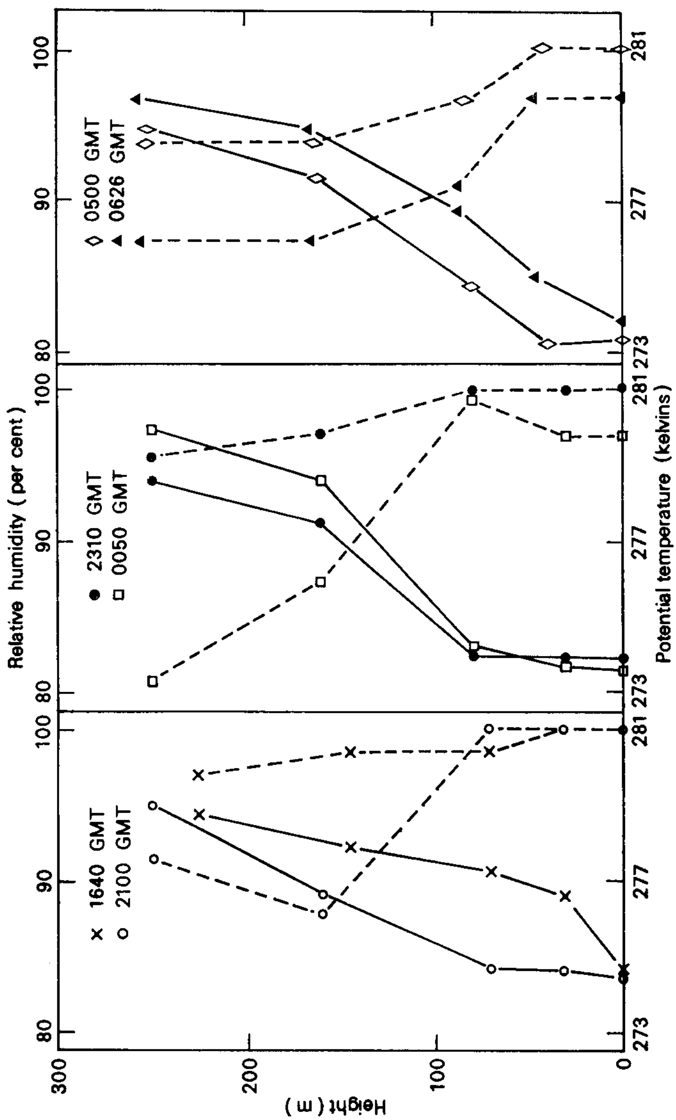

FIGURE 5—SEQUENCE OF BALTHUM PROFILES OF TEMPERATURE AND HUMIDITY FOR 14/15 NOVEMBER 1976

—— Potential temperature - - - - Relative humidity

The time of the second profile should read 2038 GMT and not 2100 GMT.

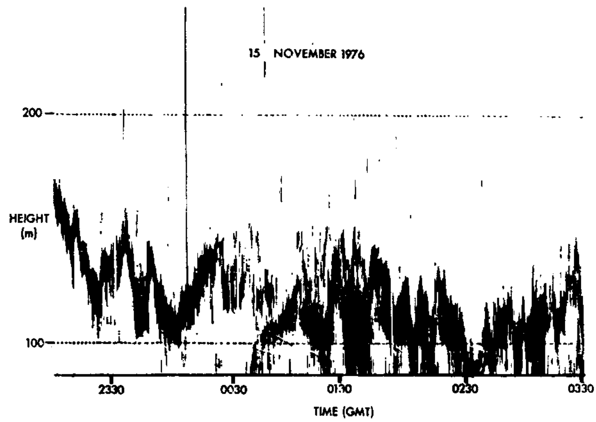

FIGURE 6—VARIATION OF THE ACOUSTIC SOUNDER LAYER ECHO-HEIGHT WITH TIME ON THE MORNING OF 15 NOVEMBER 1976

ASIMAKOPOULOS, D. N., COLE, R. S., CAUGHEY, S. J., MOSS, S. M. and READINGS, C. J. 1975 A comparison between acoustic radar returns and the direct measurement of the temperature structure of the atmosphere. *Atmos Environ*, **9**, pp. 775–776.

BARTHRAM, J. A. 1964 A diagram to assess the time of fog clearance. *Met Mag*, **93**, pp. 51–56.

CAUGHEY, S. J., CREASE, B. A., ASIMAKOPOULOS, D. N. and COLE, R. S. 1978 Quantitative bistatic acoustic sounding of the atmospheric boundary layer. *Q J R Met Soc*, **104**, pp. 147–161.

CREASE, B. A., CAUGHEY, S. J. and TRIBBLE, D. T. 1977 Information on the thermal structure of the atmospheric boundary layer from acoustic sounding. *Met Mag*, **106**, pp. 42–52.

GILMAN, G. W., COXHEAD, H. B. and WILLES, F. H. 1946 Reflection of sound signals in the troposphere. *J Acoust Soc Amer*, **8**, pp. 274–283.

HAUGEN, D. A., KAIMAL, J. C. and NEWMAN, J. T. 1975 The use of an acoustic echo sounder for optical tracking applications. *AFCRL Instrumentation Paper* No. 239, Project 2646, Bedford, Mass.

HEFFER, D. J. 1965 A test of Kennington's method of forecasting the time of clearance of radiation fogs. *Met Mag*, **94**, pp. 259–264.

KALLISTRATOVA, M. A. 1959 An experimental investigation into the scattering of sound in a turbulent atmosphere. *Dokl Akad Nauk SSSR*, **125**, pp. 69–72.

KRAICHNAN, R. H. 1953 The scattering of sound in a turbulent medium. *J Acoust Soc Amer*, **25**, pp. 1096–1104.

LIGHTHILL, M. J. 1953 On the energy scattered from the interaction of turbulence with sound or shock waves. *Proc Cambridge Philos Soc*, **49**, pp. 531–555.

LITTLE, C. G. 1969 Acoustic methods for the remote probing of the lower atmosphere. *Proc IEEE*, **57**, pp. 571–578.

1972 On the detectability of fog, cloud, rain and snow by acoustic echo sounding methods. *J Atmos Sci*, **29**, pp. 748–755.

MCALLISTER, L. G. 1968 Acoustic sounding of the lower troposphere. *J Atmos Terr Phys*, **30**, pp. 1439–1440.

MONIN, A. S. 1962 Characteristics of the scattering of sound in a turbulent atmosphere. *Soviet Phys Acoust*, **7**, pp. 370–374.

NEFF, W. D. 1975 Quantitative evaluation of acoustic echoes from the planetary boundary layer. *NOAA Tech Rep*. ERL 322-WPL 38, Boulder, Colorado, pp. 34.

PAINTER, H. E.	1970	The tethered radiosonde. *Met Mag*, **99**, pp. 93–98.
ROACH, W. T., BROWN, R., CAUGHEY, S. J., GARLAND, J. A. and READINGS, C. J.	1976	The physics of radiation fog: I—a field study. *Q J R Met Soc*, **102**, pp. 313–333.
TYNDALL, J.	1874	On the atmosphere as a vehicle of sound. *Philos Trans R Soc*, **164**, pp. 183–244. Also Tyndall, J. Sound (3rd edition) 1875.

551.509.313:551.577.51

THE FORECASTING OF OROGRAPHICALLY ENHANCED RAINFALL ACCUMULATIONS USING 10-LEVEL MODEL DATA

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SUMMARY

A diagnostic model has been developed in order to estimate the effect of orography on surface rainfall accumulations. The model calculates rainfall amounts at grid points 3¾ km apart using large-scale input parameters forecast by the fine-mesh version of the Meteorological Office 10-level model. The performance of the orographic model during a two-week trial period is assessed.

1. INTRODUCTION

A major problem in the provision of short-period weather forecasts is the estimation of local rainfall which may be modified by local topographic effects. An important operational requirement is the forecasting of rainfall accumulations in hilly areas (Holgate, 1973). Methods of forecasting based on the extrapolation of the movement of precipitation echoes derived from radar observations (Hill, Whyte and Browning, 1977) are only useful for forecasting up to 6 hours ahead, and even these forecasts will require modification if the local orographic effects are large. For forecasts up to 36 hours ahead a numerical model is required. Unfortunately the resolution of present numerical models is one or two orders of magnitude greater than the scale of the orographic features, and the effect of these features is not incorporated into the resulting rainfall forecasts. One solution is to use the output from a numerical model as input to a separate, numerically simple model that has a grid size small enough to resolve the orography adequately and which contains the essential physics of the orographic rainfall process.

Collier (1975) has formulated a model of orographic rainfall which provides for an elaborate method of estimating vertical velocity in the vicinity of orographic features. This model has been employed with some success to estimate rainfall accumulations in North Wales, radiosonde observations having been used as input data. As Collier (1977) indicates, the model results are only valid in special circumstances when there is efficient conversion of orographic cloud to liquid rain water. The cloud microphysical processes which are not parametrized in Collier's model play an important role in determining the extent of the orographic influence on the rainfall. The model about to be described is similar in concept to Collier's but a simpler formulation for obtaining local vertical velocity is used together with a scheme for treating the cloud physics processes. It is based on a scheme suggested by Jonas (1976). The method described by Bader and Roach (1977) for calculating the washout of droplets by raindrops from a higher cloud in a low-level orographically produced cloud has been adapted for use in this model.

2. Model features

(a) *General description*

The model has been designed to use the output from the fine-mesh version of the Meteorological Office 10-level model (Burridge and Gadd, 1977); although the latter includes orography, it is in a very smooth form. Local perturbations of the flow due to sub-gridscale variations in orography are assumed not to affect the large-scale flow, but to add an extra component to the vertical velocity and modify the relative humidity at the fixed pressure levels.

Precipitation is formed in a given layer by adiabatic ascent. It is assumed that the rate of rainfall so formed may be written as

$$P_1 = -k_1 k_2\, \omega(\partial r_s/\partial p)_{sat}\, \rho \Delta z \text{ g s}^{-1}\text{ m}^{-2}. \qquad (1)$$

This is similar to the expression derived by Collier (1975); $\omega = dp/dt$ is the vertical velocity in p co-ordinates, $(\partial r_s/\partial p)_{sat}$ is the derivative of saturated humidity mixing ratio with respect to pressure for a saturated adiabatic ascent, ρ is the air density and Δz the thickness of the layer or, in the case of the lowest level, the height of the level above the surface. The derivation of the parameters k_1 and k_2, which depend on the way in which the relative humidity is modified by ascent, will be described in section 2(c).

Precipitation falling into the next layer is enhanced by the accretion of cloud water. This washout process increases the rate by P_2 to give a total rate of rainfall $P = P_1 + P_2$, where we assume that P_2^j is a function of P^{j-1}, the precipitation rate in the layer (j–1) above, and of q^j, the cloud liquid water content in the layer j. Details of this process will be considered later in section 2(d). The surface rainfall is calculated by summing the contributions from five 100 mb layers, from the surface to 500 mb.

The large-scale velocity components (u, v, ω), the layer thickness Δz, and the humidity mixing ratio r, available from the 10-level model are interpolated to the orographic model grid points whose resolution is 3⅓ km. The orographic height is defined at each point.

(b) *Formulae for vertical velocity and* $(\partial r_s/\partial p)_{sat}$

A simple parametrization of the effect of orography has been adopted. The vertical velocity ω is given by

$$\omega = \omega_L + \omega_T \text{ mb s}^{-1}, \qquad (2)$$

where ω_L is the large-scale vertical velocity and ω_T is an orographically induced component assumed to be proportional to the scalar product of horizontal velocity $\mathbf{V}$ and local topographic gradient ∇H, that is

$$\omega_T = -k_3\,(\mathbf{V}.\nabla H)\,\rho g \text{ mb s}^{-1}. \qquad (3)$$

The effect of orography is assumed to reduce linearly to zero at 500 mb. Accordingly the factor k_3 varies linearly with the height of the level above the surface, from zero at 500 mb, to unity at the surface. This treatment is very crude but seems justified as a first attempt because the overall accuracy of the forecast is dominated by the accuracy of the 10-level model results. The effect of stability on the magnitude and vertical extent of the ascent is also neglected.

The rate of change of saturated mixing ratio with respect to pressure along a saturated adiabat may be readily derived from thermodynamic arguments. The energy conservation equation may be written as

$$L\,\mathrm{d}r_s = c_p\mathrm{d}T + (RT/p)\mathrm{d}p, \qquad (4)$$

where L is the latent heat of vaporization and c_p the specific heat at constant pressure.

In terms of the saturated vapour pressure e_s, the humidity mixing ratio is $r_s \approx \epsilon\, e_s/p$, where $\epsilon = 0{\cdot}622$. In differential form this becomes

$$\mathrm{d}r_s/r_s = \mathrm{d}e_s/e_s - \mathrm{d}p/p. \qquad (5)$$

The term e_s may be eliminated from equation (5) by using the Clausius–Clapeyron relation to give

$$\mathrm{d}r_s/r_s = \epsilon L\mathrm{d}T/RT^2 - \mathrm{d}p/p. \qquad (6)$$

Manipulation of equations (4) and (6) gives

$$(\partial r_s/\partial p)_{sat} = r_s\,(RT/p)(\epsilon L - c_pT)/(L^2\epsilon r_s + Rc_pT^2). \qquad (7)$$

(c) *Modification of the relative humidity by forced adiabatic ascent.*

The orographically induced displacement is parametrized in the same way as the orographically induced component of vertical velocity. At a given level, the displacement is given by $H_T = k_3$H, where k_3 is as in section 2(b) and H is the orographic height.

The relationship between the final relative humidity X_f and the initial relative humidity X_i for a dry adiabatic ascent H_T is appoximately linear, i.e.

$$X_f = X_i\,\{1 + \alpha(p,T)\,H_T\}, \qquad (8)$$

where α is a function of temperature and pressure only.

The parameter k_1 (see equation (1)) is assumed to depend on the vertical velocity and the relative humidity. Thus $k_1 = 0$ if $\omega \geqslant 0$, that is where there is local descent or if $X_f < 1$ when the air is unsaturated after ascent. Otherwise k_1 is set equal to unity and precipitation is allowed to form.

The parameter k_2 is introduced in an attempt to take into account the depth of the cloud. If the air is already saturated before orographic uplift then $k_2 = 1$. The parameter k_2 is dependent on the length of time the growing droplets spend in the orographic cloud. The vertical displacement H_s to reach saturation is given by substituting $X_f = 1$ in equation (8)

$$H_s = (1 - X_i)/\alpha X_i. \qquad (9)$$

The droplets are assumed to follow the air motion with a vertical velocity $-\omega/\rho g$ m s^{-1} for the remainder of the forced displacement $(H_T - H_s)$. Hence the time taken for the droplets to grow in the cloud is given by

$$t = -\rho g/\omega\,\{H_T - (1 - X_i)/\alpha X_i\}. \qquad (10)$$

A typical time scale for droplet growth is 20 minutes, thus we assume

$t > 1200$ seconds	$k_2 = 1$
$300 \leqslant t \leqslant 1200$ seconds	$k_2 = (t-300)/900$
$t < 300$ seconds	$k_2 = 0.$

If air becomes saturated during ascent the remainder of the ascent is taken along a saturated adiabat. The final value of saturated mixing ratio r_s is derived from equation (7). Hence a new value of the relative humidity $X_f = (r/r_s)$ is found which is greater than 100%. It is used to derive an estimate of the cloud liquid water content q, assuming (i) that 10% of the condensed water is retained in the cloud and (ii) that cloud forms at 90% relative humidity.

$$q = 0{\cdot}1\ (X_f - 0{\cdot}9)r_s \times 10^{-3}\ \rho\ \text{kg m}^{-3}. \qquad (11)$$

(d) *Washout*

Now that an estimate of cloud liquid water has been made the rainfall P_2 due to accretion of cloud liquid water may be calculated. For simplicity a single cloud drop size of radius 10 μm is assumed. For a raindrop of radius a, with a fallspeed V_a, and collection efficiency E_a, the rate of accretion W' of cloud liquid water is simply $W' = E_a V_a \pi a^2 q$, since $\pi a^2 V_a$ is the volume of air swept per second. If the raindrop distribution is $N_a \Delta a$, then the total washout summed over all drops is given by

$$W = q \sum_a N_a V_a E_a \pi a^2 \Delta a. \qquad (12)$$

This expression is used by Bader and Roach in their model. $N_a \Delta a$ is defined by the 'Best' dropsize distribution which is a function only of precipitation rate (see Mason 1971). The terminal velocities and efficiency factors are also taken from Mason. The summation in equation (12) is then only a function of precipitation rate. The increase in precipitation rate is $P_2 = W\Delta z$, where Δz is the layer thickness.

Thus the total precipitation rate derived within a layer is

$$P = P_1 + P_2 = -k_1 k_2 \omega(\partial r_s/\partial p)_{sat}\ \rho\Delta z + W\Delta z\ \text{g s}^{-1}\ \text{m}^{-2}. \qquad (13)$$

This is subject to the constraint that the maximum allowable rainfall rate is $P = -\omega(\partial r_s/\partial p)_{sat}\ \rho\Delta z$.

(e) *Other features of the model*

Three other features included are evaporation, precipitation drift and spatial averaging.

If rain falls through a layer of unsaturated air, some or all of it will evaporate. The evaporation scheme uses empirically derived relationships due to Best (1952), a version of which is also used in the 10-level model. A raindrop of radius a_1 reduces to a radius a_2 when falling from height z_1 to z_2.

The empirical relation between a_1 and a_2 is

$$a_1^2 - a_2^2 = E(z_1,z_2)\ (1 - X)^{1{\cdot}13}, \qquad (14)$$

where X is the relative humidity and E is an empirical parameter derived by Best which depends on the height of the levels. The initial precipitation rate is resolved into a dropsize spectrum as in section 2(d), a new dropsize spectrum is computed using equation (14) and from this the final precipitation rate can be derived.

The horizontal drift of precipitation as it falls can have a considerable effect on the distribution of surface rainfall. Although the thermodynamics of the ice phase is not included in the model, the precipitation is considered as snow for the purposes of calculating drift if the temperature of the layer is less than 273 K. For example, the time taken for snow to fall from one level to the next is about 1000 seconds assuming a fallspeed of 1 m s^{-1}. In a strong wind of 25 m s^{-1}

the snow will have drifted 25 km (that is to say about 7 grid lengths). If the precipitation is in the form of rain with a fallspeed of approximately 5 m s^{-1}, the drift is correspondingly reduced but is still appreciable.

Finally to avoid unrealistic gradients which might arise since the rainfall rate at each grid point is calculated independently of its neighbours, a 1–2–1 smoothing operator is applied in both the x-direction and the y-direction at each internal point.

3. Results

The aim of this study has been to provide a potential forecasting model. To assess the performance of the model it was tested over an extended period, data from a 10-level rectangle forecast being used as input. The accuracy of the rectangle forecast limits the accuracy that can be expected from the orographic model; an accurate analysis of the large-scale variables is, however, difficult to obtain on an hourly basis. The method of assessment used here shows how the model would perform in practice.

The orographic model was used to provide forecasts of rainfall over Wales and central England. The area covered by the study is shown in Figure 1. The orientation of this area is the same as that of the fine-mesh 10-level model whose grid points are marked by crosses. Figure 1 also shows the orography used in the calculations and the 23 areas of size 2500 km^2 used for verification. The trial was for 14 consecutive days starting on 3 October 1976.

Throughout the period a westerly or south-westerly situation persisted with fronts and depressions crossing the British Isles, notably on the 14th when a deep depression reached south-west England and moved slowly north-east.

The input data for the orographic model were extracted hourly from the 10-level model fine-mesh forecast based on a midnight analysis. The data from $T+9$ to $T+32$ hours were used, so that the forecast period of the orographic model coincides with a rainfall day. The large-scale parameters used as input to the model were assumed to be representative of conditions for a 60-minute period and were updated each hour; 24-hour accumulations were obtained by summing the predicted hourly rainfall amounts.

The only suitable observational data with which to compare the model results were the daily rainfall totals from the national rain-gauge network. Programs developed by the hydrometeorological section of the Meteorological Office produce objective estimates of the areal rainfall totals (Shearman, 1975). They may be in error in data-sparse areas but in the absence of any other information they will be considered as 'truth'. A further problem with verification is that the observed rainfall is the sum of convective type and dynamic type. The orographic model only caters for dynamically induced ascent (both large scale and orographically induced), therefore when comparing areal totals a contribution to the total due to convective processes was included.

This convective contribution was derived from the 10-level model deep convection scheme (Hayes, 1977) which added about 20 per cent to the rainfall totals for low-lying areas. This figure is in broad agreement with reports from synoptic stations although it is probably an overestimate for inland stations.

Since the accuracy of the results from the orographic model depends directly on the quality of the forecast input data derived from the 10-level model, verification of the results would be incomplete without a comparison with the results from the present operational scheme.

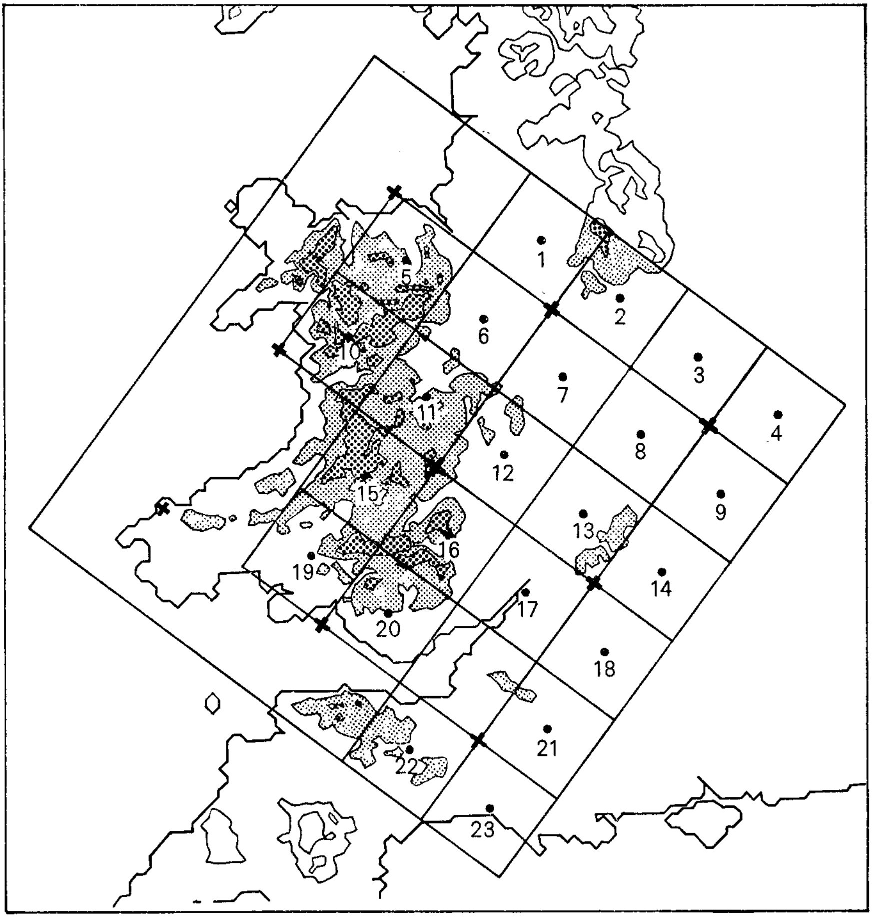
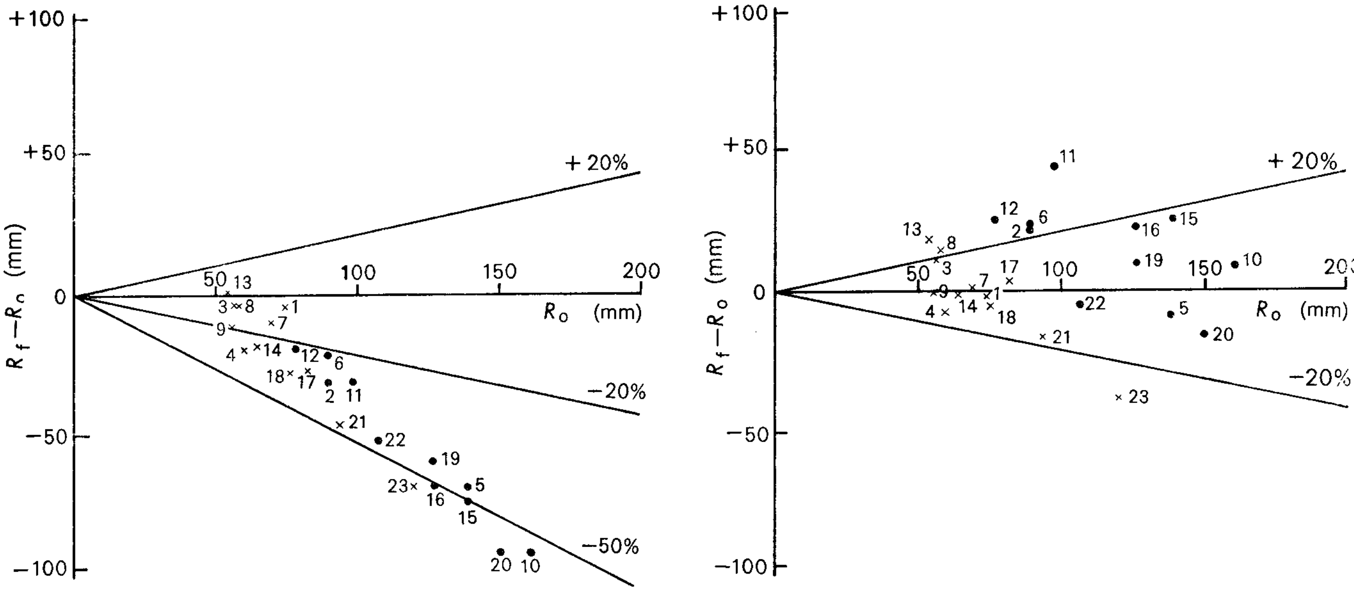


FIGURE 1—OROGRAPHY ON A $3\frac{1}{3}$ km GRID

Light shaded areas represent land between 200 m and 400 m above mean sea level.
Dark shaded areas represent land over 400 m above mean sea level.
X rectangle grid point ● centre of 50 × 50 km areas used for verification

Figure 2 shows the difference between model and rain-gauge estimates of the 2 week totals for each of the 23 areas of size 2500 km² as a function of gauge estimate. Figure 2(a) refers to the 10-level model and Figure 2(b) refers to the orographic model. The areas are numbered as in Figure 1 for reference, lowland areas being marked with crosses and areas where a significant percentage of the land is above 200 m being marked with dots. The closer the points to the x-axis the better the forecasts. Several conclusions can be drawn from Figure 2(a). It is evident that although the 10-level model forecasts rain fairly accurately for most of the low-lying areas, as the orographic influence becomes more pronounced it increasingly under-forecasts the rainfall. The improvement given by using the orographic model is greatest for the hilly areas. For the eight areas



(a) 10-level model

(b) Orographic model

FIGURE 2—PLOT OF (FORECAST RAINFALL MINUS OBSERVED RAINFALL) AGAINST (OBSERVED RAINFALL) FOR TWO WEEK PERIOD

(a) compares results from 10-level model with observed rainfall.
(b) compares results from orographic model with observed rainfall.
● hilly areas X lowland areas
The straight lines show the bounds for forecast errors of 20% and 50% respectively.

where the rainfall exceeded 100 mm in two weeks, the 10-level model under-forecast the rain by between 45 and 60 per cent. On the other hand for the orographic model (Figure 2(b)) the errors were less than 18 per cent for all but one area and five areas had errors below 10 per cent.

Figure 3 shows the daily rainfall for both models together with rain-gauge estimates for area 20 in South Wales. Figure 3(a) compares 10-level model results with rain-gauge estimates and Figure 3(b) compares orographic model results with rain-gauge estimates. Figure 4 shows a similar plot for area 5 in North Wales.

These results are typical of the results from hilly areas. For both areas the orographic model produced a better forecast on almost every day. The per centage of observed rainfall forecast by the 10-level model for area 5 was 51 per cent for the two week period compared with 94 per cent for the orographic model forecasts. For area 20 the corresponding figures were 40 per cent and 89 per cent. For all 23 areas together the rectangle forecast 62 per cent of the observed rainfall and the orographic model forecast 106 per cent.

The correlation coefficient between 10-level model daily area forecasts and observed rainfall was 0·580 over the two week period for all areas combined (322 forecasts). The corresponding correlation coefficient between rainfall forecast by the orographic model and actual rainfall was 0·702. This improvement in the correlation coefficient is 2·6 times the standard error. The mean of the absolute difference between forecast and actual rainfall

$$M_D = \frac{1}{14}\sum_{1}^{14}|(r_m - r_a)|$$

was calculated for both models and for areas 5 and 20. For the 10-level model M_D was 5·85 and 6·53 mm for the two areas respectively, compared with 3·56 and 3·03 mm for the orographic model. The difference was tested for significance using a *t*-test and the improvement was found to be significant at the 1 per cent level.

Figures 5 and 6 show the rainfall fields as depicted by the rain-gauge network and as produced by the orographic model respectively for the rainfall day commencing at 09 GMT on 14 October 1976, the wettest day during the trial period. Bearing in mind that the basic input to the model was forecast data and that those data were on a scale of 100 km so that many of the mesoscale features producing intense precipitation (such as those described by Browning *et alii*, 1974) were not defined, we see that the rainfall field forecast by the orographic model fits encouragingly well with that derived from rain-gauges. The distribution and intensity of rainfall in Snowdonia, Exmoor and Pembrokeshire is particularly good. Note the drift of precipitation over the Conwy valley to the east of Snowdon and also the accurate forecast in Pembrokeshire of an enhancement by a factor of three on fairly low hills indicating the importance of the gradient of the hills as well as their height. Although the rain-shadow effect giving drier areas to the immediate lee of the hills is fairly realistic, there is a general tendency to over-forecast the rainfall in the area to the east of the Welsh mountains and it seems that the removal of additional water by precipitation upwind may be a contributory factor. An improved scheme might be one which modifies the large-scale humidity field in the 10-level model to take into account the local removal of water by the orographic model. This would lead to a feedback

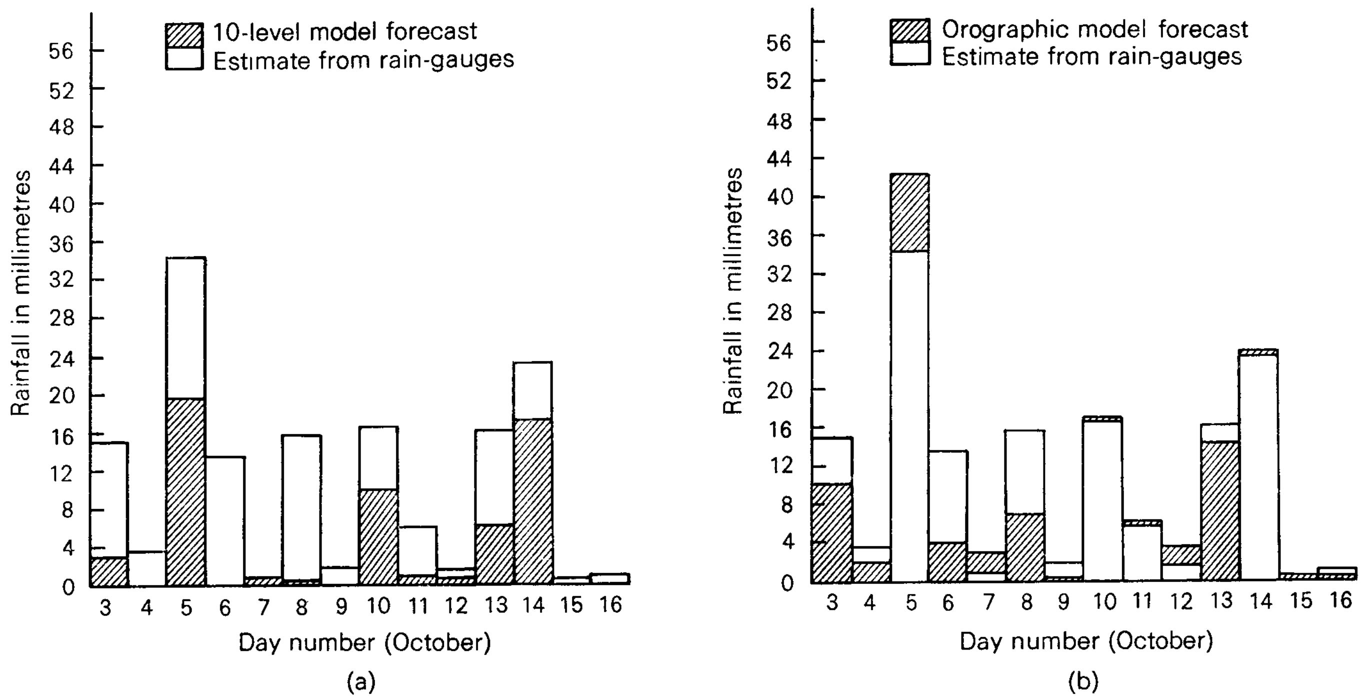


FIGURE 3—COMPARISON OF FORECAST AND OBSERVED RAINFALL IN AREA 20 (SOUTH WALES)

(a) Daily rainfall forecast by 10-level model
(b) Daily rainfall forecast by orographic model
Forecast, and estimated actual, values of rainfall are superimposed with common zero on the axis; the arrangement in the vertical of hatched and blank areas depends on which value is the greater.

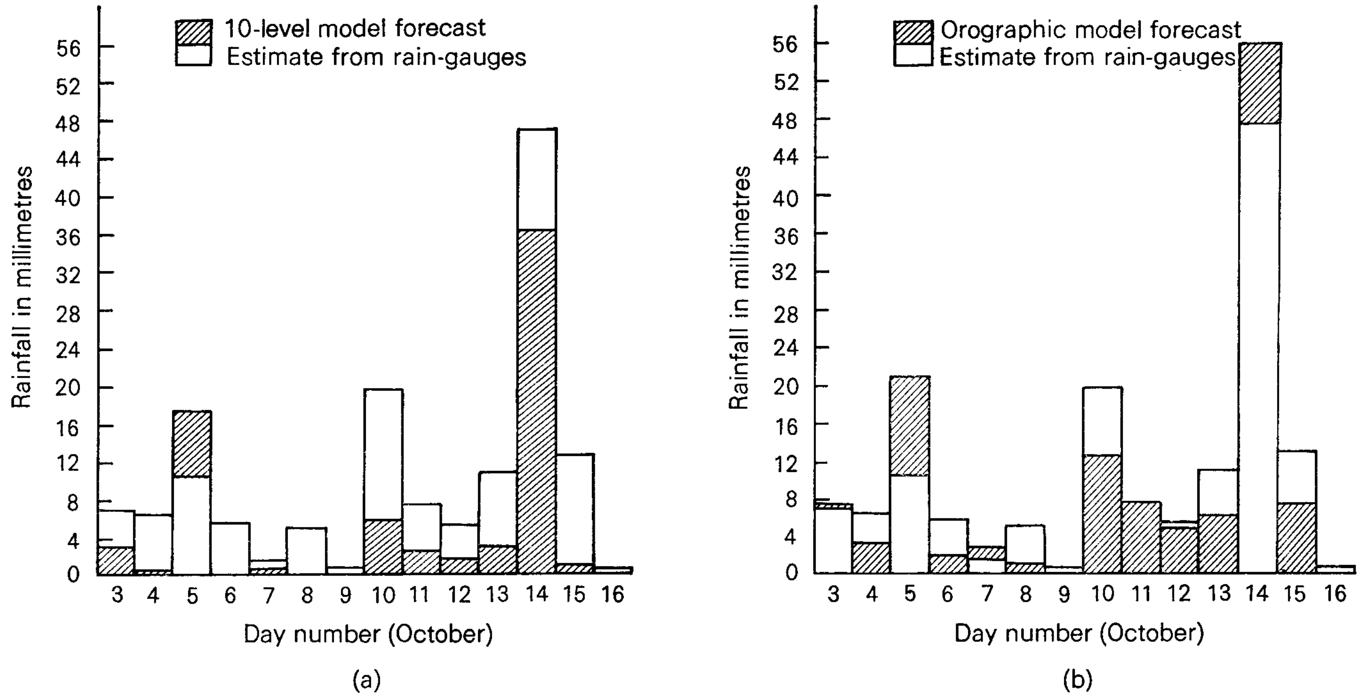


FIGURE 4—COMPARISON OF FORECAST AND OBSERVED RAINFALL IN AREA 5 (NORTH WALES)

(a) Daily rainfall forecast by 10-level model
(b) Daily rainfall forecast by orographic model
Forecast, and estimated actual, values of rainfall are superimposed with common zero on the axis; the arrangement in the vertical of hatched and blank areas depends on which value is the greater.

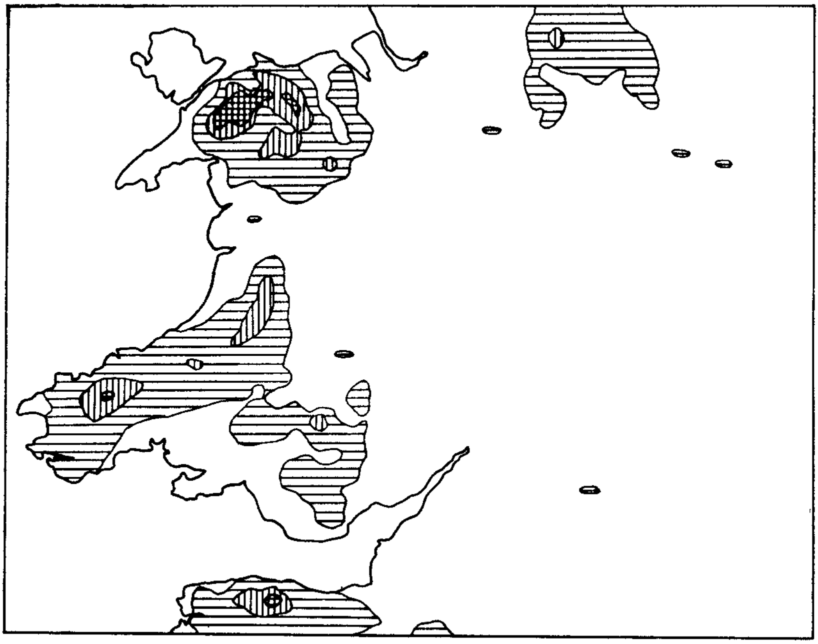


FIGURE 5—RAINFALL ESTIMATED FROM RAIN-GAUGES FOR 14 OCTOBER 1976
Horizontal hatching indicates rainfall between 25 and 50 mm, vertical hatching rainfall between 50 and 75 mm, and cross-hatching rainfall in excess of 75 mm.

mechanism between the two models. On 14 October the rain area was forecast by the 10-level model to be too far east and this is reflected in the poor rainfall forecast for the West Midlands (20 mm forecast by both orographic model and 10-level model compared with an observed 5 mm). Since this area is low-lying, the orographic contribution is minimal but a scheme for removing water as just described might have produced better results.

4. CONCLUSION

It has been shown that the orographic influence on rainfall from large-scale systems is well reproduced by this relatively simple model used in conjunction with the 36 hour forecast produced by the fine-mesh version of the 10-level model. Several improvements might be envisaged for the future. The dynamics has been treated very simply and an improved scheme on the lines developed by Collier might be of use. Inclusion of a scheme to handle orographically triggered convection and improved modelling of the rain-shadow effect would also be beneficial.

REFERENCES

BADER, M. J. and ROACH, W. T.	1977	Orographic rainfall in warm sectors of depressions. *Q J R Met Soc*, **103**, pp. 269–280.
BEST, A. C.	1952	The evaporation of raindrops. *Q J R Met Soc*, **78**, pp. 200–225.

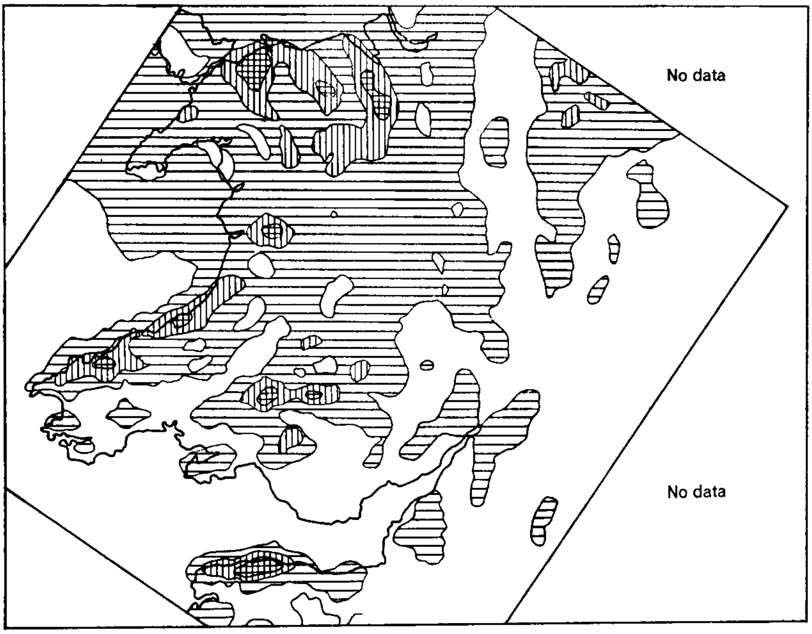


FIGURE 6—RAINFALL FORECAST BY OROGRAPHIC MODEL ON 14 OCTOBER 1976

Horizontal hatching indicates rainfall between 25 and 50 mm, vertical hatching rainfall between 50 and 75 mm, and cross-hatching rainfall in excess of 75 mm.

BROWNING, K. A., HILL, F. F. and PARDOE, C. W. 1974 The structure and mechanism of precipitation and the effect of orography in a wintertime warm sector. *Q J R Met Soc*, **100**, pp. 309–330.

BURRIDGE, D. M. and GADD, A. J. 1977 The Meteorological Office operational 10-level numerical weather prediction model (December 1975). *Scient Pap, Met Off*, No. 34.

COLLIER, C. G. 1975 A representation of the effects of topography on surface rainfall within moving baroclinic disturbances. *Q J R Met Soc*, **101**, pp. 407–422.

1977 The effect of model grid length and orographic rainfall efficiency on computed surface rainfall. *Q J R Met Soc*, **103**, pp. 247–253.

HAYES, F. R. 1977 A new parameterization of deep convection for use in the 10-level model. *Q J R Met Soc*, **103**, pp. 359–367.

HILL, F. F., WHYTE, K. W. and BROWNING, K. A. 1977 The contribution of a weather radar network to forecasting frontal precipitation—a case study. *Met Mag*, **106**, pp. 69–89.

HOLGATE, H. T. D. 1973 Rainfall forecasting for river authorities. *Met Mag*, **102**, pp. 33–38.

JONAS, P. R. 1976 A method of estimating local topographically enhanced rainfall accumulations using 10-level model forecast data. (Unpublished, copy available in Meteorological Office Library, Bracknell.)

MASON, B. J. 1971 The physics of clouds. London, Oxford University Press.

SHEARMAN, R. J. 1975 Computer quality control of daily and monthly rainfall data. *Met Mag*, **104**, pp. 102–108.

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A NATIONAL INVENTORY OF WEATHER STATIONS

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In the recording of weather and climate the United Kingdom is in the fortunate position of having a central organization for the collating of information. The Meteorological Office receives monthly returns of data from over 600 weather stations. However, it can be argued that even this great number falls well short of an adequate coverage. The problems with a network of this nature are manifold, but given strict standardization of sites, and observation times, there are three which serve to limit the effective value of the data generated:

(1) The stations do not fall into a spatially uniform pattern. Avoidance of difficult terrain such as upland or other inaccessible areas produces a distribution of weather stations which favours lowland locations, particularly those near to coasts. There are, therefore, large gaps in the overall picture of climatic variation in the United Kingdom and with such an unbalanced network, interpolation and extrapolation become necessary tools for the climatologist.

(2) The topography of the United Kingdom is well diversified, small areas containing a complex matrix of localized climates. In hilly areas for example, such as the Pennines, the modifying effects of elevation upon climate can be concealed by those arising from the other elements of topography such as aspect and slope. In such areas, an accurate impression of spatial variation in climate can only be attained from a relatively dense network of weather stations. In reality, the researcher could be considered lucky to find just one station to represent the whole of the area with which he is concerned.

(3) The spatial complexity of climatic variation is exacerbated by the great variability in time of atmospheric conditions over the British Isles. The development of the valley inversion, for example, is obviously dependent not only upon valley configuration but also upon synoptic conditions.

In the light of these problems it would appear that the Meteorological Office network of stations, while it forms the backbone of weather and climate recording in the United Kingdom, contains large gaps which it is desirable to fill. Fortunately this aim can, in some measure, be achieved through the efforts of a number of weather enthusiasts and organizations involved in weather-data collection at both local and national levels.

To some extent, however, the efforts of the weather enthusiast tend to replicate the Meteorological Office network rather than to make significant inroads into some of the larger gaps within it. Organizations such as the Climatological Observers' Link do, however, swell the reservoir of information. Observations of both quantitative and qualitative nature are exchanged between members through the vehicle of monthly bulletins. However, this organization, despite its good works, falls well short of a complete inventory of all weather stations in the United Kingdom.

Contact with research workers in, for example, hydrology, forestry and agriculture, and with teachers' groups has revealed that there is a great deal of hitherto uncollated local weather information in the United Kingdom emanating from stations which often lie in the undesired gaps to which reference has already been made. A major problem with many of these stations is that they frequently do not conform to established standards of siting and instrumentation. Many schools, for example, can only manage a five day schedule of observations. Research organizations, such as the Institute of Hydrology, often rely upon autographic methods of weather recording, occasionally using completely automatic weather stations in upland environments such as on the Cairngorms. However, if full site and instrument particulars are made available, correction can be made for any such deviation from established codes of practice.

Work on an inventory of all weather stations in the United Kingdom began in 1975 with three broad aims. These were firstly to establish the presence of all weather stations not included in Meteorological Office published lists, secondly to determine the siting characteristics of these stations and thirdly to determine the nature of the observations made. The project was named the Register of Weather Stations or ROWS.

To date, information on hitherto unrecorded weather stations has been collected by using a questionnaire method. In addition to particulars of station name, grid reference and height above sea level, the respondent is asked to assess slope, aspect and shelter on five-point scales. He is then asked to indicate whether air temperature, earth temperature, solar radiation, ground surface minimum temperature, precipitation, evaporation, relative humidity, wind speed and wind direction are recorded. The first questionnaires used were four pages long, which elicited useful information on site and instruments but which was generally regarded as being too long. This format has been replaced by one which occupies only one page and which can usually be completed in less than five minutes.

Letters outlining the work of ROWS have so far been published in the *Bulletin of Environmental Education*, *Area*, *Geography*, *Weather*, and the *Classroom Geographer;* this publicity has resulted in nearly 80 completed questionnaires. The respondents include 22 from water authorities and 31 from local weather enthusiasts, covering a wide range of geographical locations. Two issues of ROWS have already been produced, in September 1975 and January 1977.

Over the next five years it is hoped that the Register of Weather Stations project will collect information relating to most non-Meteorological Office weather stations. While funds are severely limited, growth will inevitably be slow but the organizers feel justified in pursuing what is regarded as a worthwhile goal.

We should like to point out that in the view of the Meteorological Office the process of making corrections to observations from non-standard sites is far from easy and may even be, in the strict sense, impossible. The relationships involved are non-linear and depend on all sorts of things such as wind direction, season etc.; for example, no wholly satisfactory relationship has yet been established between the temperature readings from the North Wall screen at

Kew and those from the standard screen. However, it is probably true to say that carefully made corrections to readings from a non-standard site will make them nearer than they otherwise would have been to those from a hypothetical standard site located in the same neighbourhood.

EDITOR

REVIEW

Drought and Agriculture (*Report of the CAgM Working Group on the Assessment of Drought*), *WMO Technical Note*, No. 138, prepared by C. E. Hounam (Chairman), J. J. Burgos, M. S. Kalik, W. C. Palmer and J. [C.] Rodda. 275 mm × 210 mm, pp. xv + 127, *illus.* Secretariat of the World Meteorological Organization, Geneva, Switzerland. Price: 30 Sw. Fr.

This *Technical Note* is concerned with the complex subject of the effect of drought on agriculture, and on the whole succeeds well in highlighting the problems which must be considered in any analysis of agricultural drought. In particular it points out the distinction which must be drawn between 'aridity' and 'drought', since the agriculture of an area will have developed in such a way as to cope with the 'normal' situation, even if this means that there are long periods in each year when little or no rainfall occurs. Attention is drawn to the fact that rainfall is not the only determining factor in the timing and severity of a drought, but that evapotranspiration and soil moisture storage must also be taken into account, particularly in areas, such as the British Isles, where there is a large variation between winter and summer values of potential evaporation. The effects of drought depend also on the crop concerned, on its rooting characteristics, length of growing season, response to soil moisture stress and high levels of evaporative demand, and crop management.

The first three chapters contain a number of basic definitions and also examples of indices of agricultural drought. More complete details of these indices are given in Appendix I. Chapter 4 is concerned with methods of analysis of climatological data for drought studies. These chapters would provide the non-specialist in agricultural meteorology with a useful introduction to the subject, and make him aware of the still unsolved problems.

Chapters 5–9 deal with topics which are likely to be studied mainly by those primarily concerned with agricultural production; they include consideration of plant adaptation to drought conditions, water requirements of agriculture (including irrigation), diseases and pests in a drought, and local environmental control.

There are extensive bibliographies at the end of each chapter. Appendix II contains recommendations for a World Climate Watch on drought under the headings of historical assessment, real-time assessment, and prediction. Results could probably be achieved quite quickly for the first two for those areas where an adequate quantitative data base exists. However, a major breakthrough in the production of reliable forecasts of weather conditions over periods of from 5 to 30 days ahead is required if prediction of the continuation or cessation of a drought is to be achieved.

A drought which seriously affects agricultural production is likely to give rise to major economic, social and political consequences. Although this *Technical Note* has been written primarily for agricultural meteorologists and climatologists who may have to assess the drought risk for particular crops in particular areas, the introductory chapter (and to a lesser extent the two which follow it) could be read with profit by anybody who is concerned with problems of food production and distribution on a local or global scale. The Note is generally clearly and logically written, and provides a useful survey of the present state of knowledge on the subject of drought and agriculture, but in some parts too much minor detail of computation procedures is included, whilst elsewhere not enough information on basic assumptions is given.

MARJORY G. ROY

NOTES AND NEWS

Snow Survey of Great Britain

Survey Reports up to and including that for the 1967/68 season were published in *British Rainfall*. In future, Reports will be produced independently, normally in December each year. The Report for 1976/77 is now available from Meteorological Office Met O 3(b), London Road, Bracknell, Berks. RG12 2SZ at a price of £2 (post free) or a three-year advance subscription is offered at £5. Limited numbers of copies of the Reports for 1968/69 to 1975/76 are also available on application at a price of £1 per copy.

THE METEOROLOGICAL MAGAZINE

NO. 1269 APRIL 1978 VOL. 107

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

Complete volumes of 'Meteorological Magazine' beginning with Volume 54 are now available in microfilm form from University Microfilms International, 18 Bedford Row, London WC1R 4EJ, England.

Full size reprints of out-of-print issues are obtainable from Johnson Reprint Co. Ltd, 24–28 Oval Road, London NW1 7DX, England.

Issues in Microfiche starting with Volume 58 may be obtained from Johnson Associates Inc., P.O. Box 1017, Greenwich, Conn. 06830, U.S.A.

Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1 monthly **Annual subscription £13.14 including postage**

Dd. 595890 K15 4/78

ISBN 0 11 724798 7
ISSN 0026–1149

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Met.O.915
METEOROLOGICAL OFFICE

the meteorological magazine

MAY 1978 No 1270 Vol 107
Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.915

THE METEOROLOGICAL MAGAZINE

No. 1270, May 1978, Vol. 107

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THE FUTURE DEVELOPMENT OF THE METEOROLOGICAL OFFICE

By the Director-General, B. J. MASON, C.B., D.Sc., F.R.S.

SUMMARY OF DEVELOPMENTS OVER THE LAST TEN YEARS

A great many changes have taken place in the Meteorological Office during the last decade. The Weather Service has been extensively modernized and reorganized around the very powerful IBM 195/158 computer system and the automated telecommunication complex, the forecasting now being firmly based on the most advanced numerical models in operational use. Supporting services, for example observational practices and instrument research and development, have also been reorganized and strengthened. New branches have been established for hydrometeorology and for systems development. There has been a major expansion in research, with new and powerful groups established in cloud physics, geophysical fluid dynamics, satellite meteorology, stratospheric dynamics and chemistry and radar meteorology. The Meteorological Research Flight has been greatly strengthened by the acquisition of the superbly equipped Hercules flying laboratory. Our effort in the numerical modelling of weather and climate stands comparison with that of any other single institution in the world. Recruitment, especially of young scientists, has improved dramatically and much of our scientific progress is being made by scientists still in their twenties or early thirties. Our accommodation has greatly improved with the building of the Richardson Wing and the laboratory at Beaufort Park. On the international scene we have been major participants in World Weather Watch (WWW) and the GARP Atlantic Tropical Experiment (GATE) and will be making a substantial contribution to the forthcoming First GARP Global Experiment (FGGE) in 1978–79. Most important of all, we have expanded and improved our services to aviation, industry and the general public and have achieved much greater efficiency and productivity as is illustrated by the following statistics:

	1965/66	*(1977/78 estimated)*
Gross budget	£7·2 million	£28·2 million
Revenue	£1·7 million	£8·7 million
	1965	*1977*
Non-industrial staff	3159	2970
Aviation forecasts	1·24 million	2·18 million
Non-aviation enquiries	1·16 million	1·97 million

Climatological enquiries	9819	28 986
Calls on ATWS	7·75 million	19·04 million
Telecommunication traffic at Bracknell (groups/day)	1·06 million	3·32 million
FAX charts/day	274	1303

We may now fairly claim to be, in many ways, one of the most advanced and efficient meteorological services in the world, while our scientific contribution is surpassed only by the United States. All this has been achieved on a budget which has grown very little in real terms over the period and by a staff which is rather smaller now than ten years ago. But this is no reason to rest on our laurels; there is still much to be done; the major problems of meteorology are still unsolved. In the harsh economic climate that now prevails we must do even better by sharpening our objectives and making sounder and harsher judgements of priorities. In a rapidly developing science we must have some growth points even if this means hard pruning of less important projects.

Major projects in course of completion

Of the major projects in the first 10-year plan only the following are outstanding:

(a) *The Mark 3 radiosonde*

The lengthy delays in this project have been somewhat disappointing but most of the problems have now been overcome and the first station, Aughton, was commissioned in November 1977 and Crawley in February 1978. Thereafter the remaining UK stations will be installed at monthly intervals. The whole program should be completed by mid-1979.

(b) *Phase III of the automated telecommunication system*

Phase III of the automated telecommunication system, designed around a pair of Ferranti Argos 700S computers that will supplement the present Marconi Myriads, will provide a much more powerful and flexible facility capable of handling transmission speeds of 4800 bits/s on the Main Trunk and other major circuits. Facilities for the transmission of grid-point data, digital facsimile, bulletin compilation and editing and message routeing will be greatly increased. There has been some delay because of the difficulties experienced by Ferranti in the software development but the complete system should be delivered in the summer of 1978 and be fully operational by early 1979.

(c) *METEOSAT and TIROS N satellite programs*

The first flight model of the European geostationary satellite (METEOSAT) built and operated by the European Space Agency was launched in November 1977. The only serious worry concerned the Darmstadt ground station for controlling the satellite and processing the meteorological data, where the ICL 2980 twin computer system was seriously delayed because of incomplete and unsatisfactory software. However, the worst problems have been overcome and pictures from METEOSAT were received within a few days of launch. The pictures are of high quality and should provide valuable data for research and forecasting.

Funds for the operation of the first satellite throughout its useful life now seem assured but there is no provision (and little immediate prospect) for the prompt launching of the second flight model, if the first should fail. This is a very serious situation because if the first satellite does fail, and urgent steps are not taken to ensure an early second launch, METEOSAT will not be able to contribute to the First GARP Global Experiment (FGGE).

It seems only logical and sensible that, if METEOSAT proves cost-effective, it should be followed by further similar operational satellites forming part of WWW well into the 1980s. But again, political and financial difficulties, centred on the fact that national meteorological services rather than the space agencies will probably have to foot the bill at this stage, have prevented any agreement or decision from being reached.

As far as UK participation is concerned, we have assumed that the costs of a long-term operational METEOSAT program would have to fall on the Meteorological Office budget and suitable sums have been inserted in estimates for the years 1980 and beyond.

Our program to provide stratospheric sounding units (SSUs) to obtain stratospheric temperature profiles from the next series of US operational polar-orbiting satellites (TIROS N) is proceeding satisfactorily. Orders have been placed for eight such units; the first has been delivered to the USA for engineering tests and the remainder should be available at six-monthly intervals. There should therefore be no difficulty in meeting the TIROS N schedule which, in any case, has been delayed and may be delayed further by the failure of the US manufacturer to produce a satisfactory tropospheric sounding unit (TSU) with which our SSU will be integrated. Strong efforts are being made to launch the first TIROS N by mid-1979 during the operational phase of FGGE.

Our new satellite receiving station at Lasham will enable us to receive all the required satellite pictures and some of the sounding data from both METEOSAT and TIROS N but we shall need to mount a substantial data-processing effort in order to evaluate the quality of the products and use them in day-to-day operations. This is well in hand.

New objectives and programs

The scope for overall expansion of our activities will be severely limited by the current economic situation, at least for the next few years, so that new projects will require strong justification and will, in general, be possible only if some existing and less promising projects are curtailed. The review, assessment and monitoring of all our major activities and projects will be the responsibility of the new Program Review Committee. Its task will be to decide scientific priorities, achieve a proper balance between services and research, assess the benefit of projects in relation to their cost, and ensure the most efficient utilization of available resources. It will also provide the main guide-lines for the preparation of detailed estimates for ten years ahead. A comprehensive Operational Plan for the next decade is now being prepared and will set out all our major activities, programs and projects in both functional and organizational patterns.

Our main objectives must continue to be the improvement of weather forecasts in accuracy and in range, to improve their presentation and dissemination both to specialized users and to the general public, and to extend and improve our tailor-made services especially where these can earn substantial additional revenue. The recent upsurge in interest in the causes and economic impact of climatic variations is likely to continue and to call for increased climatological advice and research into possible natural and man-made climatic changes.

Increasing concern with the environment is likely to require more work on the transport and transformation of pollutants in the atmosphere including studies of their sources and sinks. The need to improve agricultural output and productivity should lead to greater demand for meteorological advice in connection with land use, development of new varieties, and control of crop and animal diseases. Other areas where meteorology can be expected to play a more important role are energy conservation and development of new sources, for example solar, tidal and wind power.

However, we must not be concerned solely with solving immediate problems. It is essential for the Office to maintain a strong base of knowledge and skills over practically the whole field of meteorology so that we can respond quickly and effectively to new demands and problems of national or international importance. Just as the original 10-year plan did not envisage such major developments as COMESA, METEOSAT, TIROS N instrumentation, and the demands of the offshore oil industry, so this new plan is unlikely to foresee all the new developments and demands of the next decade. It is therefore most important for the Office to maintain a strong research effort especially as no other organization in the United Kingdom or indeed in Europe can match our range of expertise and resources.

We should, in general, be ready to make these resources and skills available to any body, official or private, willing to pay for them, provided only that the work makes good scientific sense and does not detract unduly from higher-priority tasks. We should do more to publicize our expertise and to bid for environmental projects having a major meteorological content, the overall objective being to ensure that the Office makes a maximum contribution to the national economy.

Forecasting for a few days ahead

In recent years, owing largely to the introduction of objective numerical models, the accuracy of forecasts in the 24–72 hour range has substantially improved. The overall accuracy of 72 hour predictions of surface weather is now about as good as that of the 48 hour predictions of ten years ago, and the 48 hour forecasts are now about as good as the 24 hour forecasts were then. Moreover the number of serious errors in the 24 hour forecasts (synoptic reviews) has been halved from about 13 per cent to 6 per cent whilst the proportion of 'A' markings has increased from about 50 per cent to 70 per cent.

However, there is still room for considerable improvement in the accuracy and detail of forecasts for several days ahead and this will continue to merit a substantial effort in the improvement of the models and of the observational data base. This, and the hope of extending useful numerical predictions up to a week or more ahead, are the main reasons for our substantial contributions to the First GARP Global Experiment (FGGE). Incorporation of the FGGE data into the best models that we can produce by 1980 should provide a fairly firm indication of the practical limits to atmospheric predictability and of both the minimal and optimal designs of a global observing network.

The Office is committed to processing the FGGE synoptic data for the European and African areas, to providing global stratospheric analyses, and to contributing to the new observing systems through METEOSAT and TIROS N.

Beyond 1980 our work on medium-range forecasting will have to be closely co-ordinated with that of the European Centre for Medium-range Weather Forecasts (ECMWF) which should be operational in mid-1979.

If the Centre is successful in its main aim of producing numerical forecasts for 4–10 days ahead, some major reorganization and changes in our forecasting operations may be necessary to avoid duplication of effort. However, this is not likely to arise before the mid-1980s; meanwhile the Office should press ahead with its program of medium-range forecasting until it becomes apparent that ECMWF can do the job at least as well as the Office. The potential value of reliable medium-range forecasts to such weather-sensitive industries as agriculture, building and construction, energy, offshore operations, and even to the armed services for tactical planning, is so large that we cannot opt out until the success and future of ECMWF are assured.

Short-range forecasting

Although dynamical models have produced noticeable improvements in the accuracy of forecasts for 24–72 hours ahead, they have done little to improve the accuracy of predictions of surface weather, especially of the timing, duration and intensity of precipitation, over the first 12 hours. The general public and some industries (for example agriculture, gas and electricity) require greater accuracy and detail than we currently provide for a few hours ahead when the weather is often dominated by mesoscale and small-scale systems which cannot be represented explicitly in current models. Although higher-resolution models are being developed and merit a good deal of effort, it seems that for the next few years practical improvements are more likely to result from the extrapolation of the movement and development of precipitation patterns observed by radar and high-resolution satellite pictures.

The Chester-Dee experiment has established that rainfall over an area of radius of about 100 km can be measured not only continuously and in real time but more accurately by a single radar than by an economically feasible network of automatic rain-gauges. A linked network of about 12 radars might therefore provide continuous measurement of rainfall across the whole country and, at the same time, a complete storm detection and tracking system that could form the basis of a short-range forecasting service.

An experimental mini-network of three radars is now being installed at Camborne, Clee Hill and Upavon. The digitized output of the three radars will be composited to form a single rainfall map with rainfall intensities shown in eight colours on a television screen that can be updated every few minutes. The output may be transmitted by telephone line to any forecast office and in the first instance will be received in the Main Meteorological Office at Gloucester where a special short-range forecasting unit will be established to exploit the technique in conjunction with satellite pictures (half-hourly pictures from METEOSAT and very-high-resolution pictures from NOAA orbiting satellites) received at Lasham. This experimental network is expected to be operational in April 1978; later it may be extended to incorporate radars in the Thames Valley (covering London) and at Shannon and in Jersey.

A few years' trials should demonstrate the value of such a service, after which we contemplate a national network, jointly funded by a number of organizations including the Office, and based on a new set of unmanned radars, the first of which is now being ordered by the North West Water Authority primarily to help in the regulation of dams and reservoirs and in flood control.

Studies of changes in temperature, humidity and wind associated with the development and passage of mesoscale weather systems, aided by a closer network of automatic stations, may also lead to improved short-range forecasts of temperature and wind which, from many points of view, for example consumption and conservation of energy, are more important than precipitation forecasts.

An important requirement of such a short-range warning and prediction system will be the rapid dissemination of these 'perishable' data to the customer and here we look forward to utilizing such systems as Viewdata and Ceefax. We are actively collaborating with the Post Office in the use of Viewdata for this purpose and hope that this will be a significant source of revenue. Besides providing an operational service, the radar/satellite system should provide much valuable data for research on the structure and development of mesoscale systems and input for new dynamical models.

Long-range forecasting

The present long-range forecasts, of which about two-thirds show some positive skill, appear to have reached a plateau in performance and there seems little prospect of a substantial improvement by continued application of the present empirical, largely analogue, methods. Research will continue with the object of refining the selection of analogues and other predictors and increased attention will be given to the production of seasonal forecasts which are probably not much more difficult or much less accurate than the monthly predictions.

However, in the longer term, we must look to dynamical methods for future progress where we have some reason to believe that the outputs of numerical models, perhaps averaged over several days, will provide a better guide to the general trends of the weather over weeks and months. Forecasts based on this approach are likely to require large amounts of computer time; they might, for example, call for several integrations to 50 days each week to determine those features that can be considered 'stable'. Experiments to assess long-range forecasts on this basis are now in progress and will form part of the case for more powerful computing facilities. They could lead to the introduction of operational forecasts by 1980.

Specialized services for industry

Every effort should be made to expand and improve our specialized services to industry, the public utilities and commerce and thereby make a maximum contribution to the national economy and to increase our revenue. The Office has become more commercially minded and cost-conscious in recent years and has increased its revenue from £2 million in 1969/70 to an estimated £8·7 million for the current year, an increase from 21 per cent to 30 per cent of gross expenditure. Among the new services introduced in recent years, the income from ship-routeing and ocean tows has increased from £6000 in 1968/69 to £66 000, from the offshore oil and gas industry from £30 000 (1969/70) to £600 000, for hydrometeorological services from only £2600 (1973) to £47 000, and for climatological services from £14 400 (1974) to £45 200. The revenue from our largest customer, civil aviation, has increased from £1·5 million (1971/72) to £6·8 million.

The main problem is how to maximize revenue while maintaining an adequate and basically free service which the public has always had and will continue to demand. Within the constraints of a government department providing a public service, which are more limiting than those of a wholly commercial organization, we must become more aggressive in marketing our wide range of services and expertise and convince potential customers of the benefits of paying for a tailor-made service compared with the free but less specific and detailed advice available through the mass media. We must also show that we can provide a better service than the private consultants who have gained a foothold in some areas, in some cases by using our data and forecasts. In order to be fully competitive the Office's much greater expertise and facilities may not be sufficient; we must be able to respond flexibly and quickly to urgent requests for help and have staff available at short notice to deal with emergencies and important tasks such as tows of oil-rigs, environmental accidents, profitable overseas consultancies and so on.

Although the Office has the lion's share of the market in forecasting for the offshore industry, providing services for some 50 sites, there is still scope for expansion. The demand for ship-routeing has failed to grow as fast as we had hoped, largely because of the fall in North Atlantic traffic. However, it should be possible, through aggressive marketing and competition with commercial agencies, to build and maintain this service at the level of at least 300 routeings a year. This, together with the increasing income from the long-distance tows of oil-rigs and platforms, should keep the service financially viable. There have also been several recent requests for weather forecasts and advice on climatological trends in distant parts of the world in connection with the production of valuable crops such as cocoa and coffee; the fact that we have operational atmospheric models and are developing global models may enable us to give such advice which is not generally available elsewhere in the world.

In summary, we should be ready to bring our resources and expertise to bear on any problem of economic importance if the customer is willing to pay the full cost. Diversification into new fields will also be prudent in order to offset a possible drop in demand for services from our traditional customers such as civil aviation, which is becoming less weather-sensitive. However, given that the Office is obliged to provide a basic free public service, the scope for increased 'commercial' business is likely to remain rather limited and it is unrealistic to expect that our revenue in real terms will increase rapidly and make the Office anywhere near self-supporting.

RESEARCH

In the main, the research program should continue along the same general lines as at present with some modest expansion during the next decade for the reasons that follow. But, in common with scientific research in the country as a whole, the overall expansion is likely to be small compared with that of the last decade. So, if we are to tackle new problems and seize new opportunities, it will continually be necessary to review priorities and to be ready to curtail outmoded or less promising projects in order to support new growth areas. However, the central problems of meteorology still await solution and so the basic pattern of our research is not likely to undergo drastic changes though there may well be changes of emphasis and priority from time to time.

A continuing high level of research into basic atmospheric dynamics and numerical weather prediction will be required to meet the demand for weather forecasts of greater accuracy and range discussed earlier. More emphasis will be given to the study of mesoscale systems which are likely to be of dominant importance in short-range forecasts. We should also devote more effort to long-range forecasting on a monthly/seasonal time-scale, especially to the development of dynamical methods in the hope that these may eventually replace the current empirical and largely subjective techniques. Further improvement of 1 to 10 day predictions will depend not only on the development of better numerical models with better representation of the physical processes such as cloud and radiation, but on better (global) observations and, in the limit, by the inherent predictability of the atmosphere on these time-scales.

Concern with the environment and the possible effects of man-made activities on weather and climate is likely to persist and to become of increasing political and economic importance. The Office should therefore give increased attention to understanding the physical basis of climate and to developing models to simulate, and perhaps eventually to predict, climate changes both natural and man-made. This will almost certainly necessitate greater attention to the interaction between the oceans and the atmosphere and the development of joint atmospheric–oceanic models. This will require some considerable expansion of the Dynamical Climatology Branch.

All weather and climate models need better representations of transfer processes in the atmospheric boundary layer, a better understanding of which is also essential to the elucidation and prediction of transport and transformation of pollutants in the atmosphere and the oceans. A larger scientific effort in this field, especially in the Boundary Layer Research Branch, is indicated.

An increased effort to observe, model and predict the dynamics and chemistry of the stratosphere and lower mesosphere will be required to assess the risks to the ozonosphere from various man-made chemical compounds—another issue which is not likely to die away quickly.

A new Branch or group is planned to study the dynamics and chemistry of the stratosphere and mesosphere, building on the expertise gained during the highly successful COMESA project. The monitoring of active chemical species in the high atmosphere is likely to be a continuing requirement. If the satellite radiometer now being built by the Oxford University group for flight on NIMBUS 6 in 1978 proves suitable for this purpose, the Office might contemplate developing operational versions of this instrument for long-term global monitoring, perhaps in collaboration with the USA.

The numerical prediction of the sea-state, especially of waves and swell, will be of increasing importance and value to the offshore industry and for the routeing of ships and long-distance tows of oil-rigs. The development of a suitable model, linked to our fine-mesh atmospheric model, is likely to become an operational requirement in the near future.

The evolution of both military and civil aircraft is likely to present new meteorological problems and to resurrect some old ones, for example fog, low-level turbulence, low-level wind shear and helicopter icing, and we must try to anticipate these well in advance of the operational requirement.

There is room for the Office to make a much greater contribution to agriculture, the most important and one of the largest of our industries. Although we have had notable successes, for example in the prediction of crop and animal diseases, there must be much greater scope for assisting this highly weather-sensitive industry with a total production exceeding £3 thousand million. This may require a good deal of missionary and educational work on our part.

An increased program of global modelling for both extended weather forecasting and climate simulation, together with our investment and interest in GATE, will require an expanded effort in tropical meteorology. Our initial success in developing an operational tropical forecasting model for GATE might well be exploited to produce daily forecasts for certain tropical regions such as Africa for which additional observations will be supplied by METEOSAT. Interest in such forecasts is already being expressed by UK companies trading in such volatile and expensive commodities as cocoa and coffee.

Only the Meteorological Office, outside the United States, has the facilities, scientific manpower and expertise to tackle many of these problems on a scale sufficient to make real progress and to provide a judgement, independent of the USA, on many of the controversial and politically sensitive issues mentioned above. This, together with the economic and social value of improved weather advice and other meteorological information, is likely to provide continued firm support for our research program whilst the high quality of our young scientists should guarantee its continued success.

New facilities

(a) *Observations.* In considering new or improved facilities that will be required to fulfil the above objectives, first attention should be given to an adequate observational data base without which major investment in new models and more powerful computers may be partially nullified.

Starting with the UK observational network, the present coverage of synoptic surface stations, considerably reduced over the years by RAF closures, has serious gaps which will have to be filled mainly by automatic weather stations as envisaged in the recent review by the working group on UK networks. The nine original experimental automatic stations now being redeployed for operational use are able to make satisfactory measurements of all the synoptic parameters except cloud and present weather but the lack of cloud observations should be at least partially compensated for by the half-hourly pictures from METEOSAT and by the VHRR pictures from orbiting satellites. A further 20 stations of improved design will be installed in the next few years and up to 30 additional automatic stations, making 50–60 in all, are planned over the next ten years.

The climatological network is uneven in both distribution and quality and it is becoming increasingly difficult to rely on voluntary effort from co-operating institutions and individuals. Again automatic stations should help fill some of the gaps but finding secure sites, especially in remote areas, may be difficult.

The national rain-gauge network, consisting of some 7000 stations, also requires overhaul. A basic network of reference autographic stations should be carefully selected and maintained in consultation with the river authorities etc.; many other stations, badly sited or maintained, could probably be discontinued. Implementation of the radar rain-gauge network could make many of the stations obsolete but the basic network of telemetering rain-gauges will be required to calibrate the radars.

The long-term future of the North Atlantic Ocean Station scheme (NAOS) is likely to cause continuing difficulty and concern. The present Agreement, despite some political problems and continual protests about rising costs, will probably hold until 1981 but beyond that the future is uncertain. Our two recently refurbished ships may last for another ten years and the same is probably true of the two French vessels. The most likely outcome beyond 1981 is that the Agreement will be extended year by year until the majority of the present ships become inoperable. There is unlikely to be enough support for the building of new ships and continuing the scheme until the end of the century. We must therefore hope that satellite techniques of remote sounding will improve sufficiently during the next decade to replace the ships' observations. However, although we can look forward to improved wind data from geostationary satellites and aircraft, the outlook for satellite temperature and humidity soundings of comparable accuracy to that of radiosonde soundings is not very promising. We may therefore have to develop a dropsonde that could be deployed from commercial and military aircraft and for which the experience gained by the Cloud Physics Branch with its system should prove most valuable.

The requirements for a global observing system, in which the Office has made a considerable investment through the establishment of several new upper-air stations overseas and by our contributions to METEOSAT and TIROS N, must await the results of FGGE. Our present commitments are likely to continue mainly by contributing to a European satellite program as described above.

(b) *Computing facilities.* The present COSMOS system, based on the IBM 360/195 and 370/158 computers, has now been in continuous 24 hour operation for over six years. It is saturated, and computing time, especially for large tasks such as global circulation modelling, has to be rationed. Implementation of the scientific program described above, in particular in numerical weather prediction and the simulation of climate, will require considerably greater computing speed and memory. A case is therefore being prepared for the Office to acquire a new high-speed processor capable of operating about five times faster than the IBM 195 in 1979/80. The European Centre for Medium-range Weather Forecasts has ordered such a machine, the CRAY 1, for delivery in mid-1978 and has an experimental prototype machine installed at the Rutherford Laboratory on which to develop its programs.

Financial approval has been obtained to upgrade the present COSMOS system by the addition of at least 1 megabyte of core storage to the IBM 195 and to enhance the IBM 158 by additional memory. This, together with the new fast 'number cruncher', would provide us with a very powerful and flexible system that should meet our requirements well into the 1980s.

(c) *Telecommunications.* On completion of Phase III of the automated telecommunication complex in mid-1978, the modernization of the central system will have been largely completed. Some further rationalization and modernization of facilities at London/Heathrow Airport and HQ Strike Command are planned and there may be scope for some extension of automation into the collecting centres.

There is an urgent requirement to replace the present analogue facsimile by faster digital methods and widespread dissemination of satellite pictures, especially of half-hourly pictures from METEOSAT and VHRR pictures from polar orbiters, will facilitate local forecasting.

(d) *Aircraft.* It will probably be necessary to replace the MRF Canberra for high-altitude research during the next decade. Servicing and maintenance problems may arise if the Royal Air Force phase out the Canberras before we need to replace our aircraft. Modern methods of telecommunication and data processing should facilitate remote control of the flight and the instrumentation, making it possible to use a single-seat high-performance aircraft, without a meteorological observer.

Otherwise the MRF is well equipped and we can now look forward to a sustained program of measurement and investigation obtaining the scientific return on the major effort expended in recent years in equipping the Hercules and Canberra with modern instrumentation and data-processing facilities.

Scientific staff

The total complement of non-industrial staff is planned to reach 3000 by 1 April 1979 and to remain at that level for the next few years. Pressures to contain public expenditure and limit the overall size of the Civil Service are likely to prevail for several years and it will therefore be very difficult to achieve any significant growth of staff numbers unless there are very strong demands for additional meteorological services by customers willing to pay the full costs.

However, even within the limitations of a fixed overall ceiling, there should be considerable scope, by the reassessment of tasks and priorities, through continuing automation and improved efficiency, to implement some new projects and improve career and promotion prospects.

We have seen in the past few years a high rate of retirement from the more senior scientific grades and this, together with low recruitment of honours graduates in earlier years, has led to shortages, particularly at the Principal Scientific Officer level. The present age structure suggests that in future years the opportunities for recruitment and promotion of high calibre scientists will be more limited than in recent years and we should therefore attempt to promote as many of our very able young scientists as possible through the Individual Merit Scheme.

The situation for the forecasting and scientific support grades is, however, brighter than it has been for some time, with retirements likely to rise sharply in the next year or so and to remain at a high level for about ten years. In this category it will no doubt be possible to fill a high proportion of the large number of vacancies which will arise during the next decade by promotion of well-qualified staff from the junior grades, leaving the remainder to be filled by direct recruitment, preferably of graduates. In this area recruitment and promotion will undoubtedly be much healthier than in the past and the large movements of staff through these grades will give an opportunity for altering the proportion of staff working in different fields without major retraining programs or asking large numbers of staff to move to different fields against their wishes. It will also allow the recruitment of more specialists as necessary, for example in computer work or electronics.

Amongst the junior grades the career prospects, taking account of retirements and other losses, are likely to be much better than they have been for many years.

Buildings and accommodation

Since the total staff complement of the Office is not likely to increase significantly during the next few years, no major changes in Headquarters buildings and accommodation are planned.

The only significant expansion is likely to be at Beaufort Park where some small additions are required in the very near future followed by a modest extension of the present building during the next ten years.

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THE ROLE OF METEOROLOGY IN HELICOPTER ICING PROBLEMS

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SUMMARY

This report reviews the extent and nature of the problems created by helicopter icing and attempts to identify the role of the meteorologist both in their formulation and in their solution.

The physical problem is highlighted by a discussion of some of the processes involved in accretion. The operational problem is reviewed and the main features of the current motivation for helicopter icing research are sought.

No conclusion about the need for, or possibility of, improved weather forecasting is reached, but this is not identified as the most important area of concern. The task of the meteorologist in helping to formulate and constrain the problem through the application of physical understanding is emphasized. It is suggested that although an increased knowledge of hazard-creating processes must be sought as a matter of priority, there is also a need for an improved climatology of some relevant atmospheric parameters.

1. INTRODUCTION

The hazards created by icing on aircraft have been recognized in principle for many years. Key work in this country has been carried out by Hardy (1946), Messinger (1953), Best (1956) and Jones (1961) for example. The problems have been extensively studied abroad, particularly in the National Research Council of Canada by Stallabrass and co-workers. It is therefore rather surprising to discover the extent to which the icing of helicopters apparently continues to create significant operational problems. Thus, before attempting to discuss the role of atmospheric physics in contributing to possible solutions, it is highly appropriate to review the extent and nature of the problems being experienced.

2. THE PHYSICAL PROBLEM

In principle, ice may be expected to accrete on any surface which is below the frost-point of air in contact with it. However, this is a statement of thermodynamic possibility only, and the efficiency with which accretion actually occurs is not so simply defined. To gain an appreciation of some aspects of the problem, the energetics of ice accretion on a surface exposed to a moving airstream containing either liquid or solid water is reviewed. The analysis follows that of Jones (1961) and more recently of Cansdale and McNaughtan (1977). It is assumed that there is no heat transfer into or out of the structure whose surface temperature is of interest. The nomenclature is defined in the Appendix.

In the absence of liquid water or ice particles the surface will experience:

(a) a kinetic heating rate of $q_V = \dfrac{hr\, V_\infty^2}{2\, c_p}$

and

(b) a convective rate of heat loss of $q_c = h\,(t_s - t_\infty)$.

Thus at equilibrium the surface temperature may be expected to be some $rV_\infty^2/(2\, c_p)$ above the ambient value. At rotor-tip airspeeds of 200 m s^{-1} this excess may be $\approx$18 °C but in the central region of the blade this becomes $\approx$5 °C.

Impacting supercooled water may be assumed to warm to 0 °C and to freeze at this temperature before cooling back to an equilibrium surface temperature if this is below 0 °C. Thus there will be:

(c) a rate of heat loss in warming the impinging water to 0 °C of

$q_w = -R_w\, c_w\,(0 - t_\infty)$

where $R_w = E\, V_\infty\, W$.

Assuming the collection efficiency $E = 1$, $V_\infty = 100$ m s^{-1} and $W = 0{\cdot}5$ g m^{-3} and an ambient temperature of -10 °C, $q_w = -2{\cdot}2$ kW m^{-2}.

(d) a heat gain due to the release of latent heat on freezing this water, at a rate given by:

$q_f = R_w\, L_f = E\, V_\infty\, WL_f \approx 16$ kW m^{-2} in the above example.

(e) a sensible heat gain in cooling the accreted ice from 0 °C down to t_s of

$q_i = R_w\, c_i\,(0 - t_s) = 0{\cdot}5$ kW m^{-2} if $t_s = -5$ °C.

Additionally there will be:

(f) a heat gain due to the kinetic energy of impinging water or ice. Note that accretion is not necessary for this to be experienced. Thus:

$q_k = R_w'\, V_\infty^2/2$, where $R_w' = E_c\, V_\infty\, W$.

Therefore

$q_k = E_c W\, V_\infty^3/2$.

For $W = 0{\cdot}5$ g m^{-3}, $V_\infty = 100$ m s^{-1}, $E_c = 1$, $q_k = 0{\cdot}25$ kW m^{-2} but for $V_\infty = 200$ m s^{-1}, $q_k = 2$ kW m^{-2}, a far from negligible contribution.

(g) a rate of heat loss from the surface because of evaporation or sublimation. Thus:

$$q_e = 0{\cdot}622\, \frac{L_e\, h}{c_p}\, \frac{e_{sw} - e_\infty}{P_\infty}$$

$$q_s = 0{\cdot}622\, \frac{L_s\, h}{c_p}\, \frac{e_{si} - e_\infty}{P_\infty}$$

depending upon t_s. It is not always obvious which expression should be used but fortunately the difference between them is normally much less than either. For an object of $\approx$10 cm diameter, whose surface temperature is -5 °C, moving with a velocity of 100 m s^{-1} relative to an airstream of -10 °C, there will be a rate of heat loss due to evaporation or sublimation of $\approx$ 0·4 kW m^{-2}. This may be compared with a simultaneous convective rate of heat loss of $\approx$ 1 kW m^{-2}.

The above review demonstrates that there are a number of terms which, at typical rotor airspeeds and liquid water content, create heating or cooling rates of the order of 1 kW m^{-2}. However, the latent heat term has a dominant effect down to quite low water contents. An important corollary of this is that the thermal effectiveness of accreted particles is crucially dependent upon the phase of water substance from which they are formed. Quite low concentrations of either phase in the presence of significant quantities of the other can have a profound effect upon whether or not ice is accreted.

The situation is further complicated by proper consideration of the collection efficiency, E, so readily assumed above to be unity. In fact, the collection efficiency is itself the product of a collision efficiency E_c (the probability that a collision will occur between a surface element and a drop or ice particle) and an accretion efficiency, E_a (the probability that the surface will retain the mass of the drop or ice particle). If run-back is neglected (see below) it is probably safe to assume that $E_a = 1$ for water drops. This is certainly not so for ice particles, whose adhesion is dependent in an essentially unknown manner upon the amount of liquid on the surface. The collision efficiency, E_c, is a function of the inertial and viscous forces acting upon the particle. Langmuir and Blodgett (1946) considered this problem in relation to drops colliding with cylinders. It is inappropriate to consider the detail of their results and those of later workers who studied more representative airfoil shapes, for example Brun (1957) except to note that, in general, the smaller the particle and the larger the characteristic dimension of the collecting object the smaller is the collection efficiency. In addition it is important to recognize that for drops in the range 10 to 30 μm diameter and (for example) cylinder diameters in the range of a few centimetres to a metre, the collection efficiency is a sensitive function of these dimensions. It is unfortunate that these ranges include that part of the cloud droplet spectrum containing a significant fraction of the total water content and the scale size of aerodynamically sensitive structures.

Finally, the problem of water run-back and of the rate of cooling and mass accretion (not simply equilibrium values) create a further level of difficulty by controlling the form and strength of the accreting ice. Such problems are most unlikely to yield to any formal analysis and will probably be resolved, if at all, by empirical methods.

3. The operational problem

This centres around the need to achieve a required aviation activity at an acceptable level of risk. The risks are created by a number of hazards. Even if the amount of icing were entirely predictable, various structures differ in both their catch efficiency and their ability to withstand this accretion whilst fulfilling their aviation role. It is reasonable to expect that a given helicopter type will be sensitive to a range of hazards created by icing on the airframe, engine intake, rotor blades, windscreen etc., that different helicopter types will experience problems to differing degrees in these areas and that, although some aspects of icing are likely to be common to both fixed and rotary wing aircraft, there are likely to be significant differences also.

The basic approach employed at present is that of avoiding risk by prohibiting flight in atmospheric conditions which could cause hazard. Implementation of the policy is of course fraught with practical difficulty. There is an implication that hazardous conditions can be specified *and* forecast with sufficient accuracy to maintain a useful operational 'window'. It is the pressure of these practicalities which manifest themselves as the current level of interest in the basic problem. There is a measure of urgency created by the military role of helicopters, particularly at sea in the anti-submarine role. Such an interest is historically very natural for the United Kingdom but this has been strengthened by the growing economic significance of the North Sea area. The pressures arising from the civil use of helicopters also owe part of their origin to the need to supply the North Sea oil industry. In any event, it is very natural that both civilian and military users seek the maximum possible operational window. This in turn implies that forecasting of hazardous conditions, in the sense of generating warnings of hazardous areas at specific times, can only be an interim measure. Opinions differ on the extent to which improvements in such forecasts are necessary or indeed possible at present. The long-term aim of military operators at least, is to seek an all-weather capability. Thus the fundamental operational requirement is for data from which hazards can be predicted, protection systems designed and the widest possible cost-effective clearances be given. The question of improved forecasting is considered again below.

4. Current position

The methodology adopted hitherto in the United Kingdom, in response to this fundamental requirement, has centred around the trials concept of exposing helicopters to presumed hazardous conditions and observing the ensuing effects. The aim is to discover both the vulnerability of the specific, perhaps partly protected, helicopter and to define the atmospheric conditions which are causing problems. Most of these trials have been undertaken in the free atmosphere with and without attempts to modify the test environment through the use of spray rigs. However, some controlled experiments on specific items, under simulated conditions, have been attempted in so-called icing wind tunnels for example. The free atmosphere trial implies excellent instrumentation on the helicopter to monitor the creation of hazards and to define the specific meteorological conditions causing them. The lack of control over the environment also requires a long sequence of trials to sample the possible range of variables. When it is realized that, even today, there is almost a complete lack of adequate instrumentation to measure accretion rates and that the helicopter is far from an ideal vehicle for making free atmospheric measurements, it is not too surprising that very little physical insight into the fundamental problems has been achieved by this approach. When these difficulties are combined with the logistic problems of operating the trials technique, often outside the United Kingdom, with the full range of helicopters in service and under development, whilst trying at the same time to assess various de-icing or anti-icing techniques, it is surprising that *any* progress has been made on the typical time-scale of aircraft procurement to obsolescence. Perhaps this is reflected in the limited 'clearances to fly' in icing conditions which have been achieved so far.

The wind tunnel trial implies that the range of atmospheric variables in combination can be specified and created well enough to allow representative simulation. Unfortunately, without adequate guidance from free atmosphere experiments and data, this begs the question and preoccupation with introspective experiments, having little to do with real problems, is a distinct possibility.

Nevertheless, if progress is to be made in understanding the processes by which ice accretion actually causes hazards it must be through proper application of the above methods. The atmospheric scientist has hitherto tended to respond to specific queries from those concerned with the helicopter icing problems, often with an inadequate notion of the basic problem and an uncertainty about whether or not the query is correctly formulated. There is evidence of this in the lack of agreement over the possibility of improved forecasting methods, for example.

Finally, in returning to the question identified in the introduction, the motivation for the particular concern in helicopter icing at present has its roots in

(a) both the military and civil need for the widest possible operational capability in areas whose climates are likely to create hazardous conditions;

(b) the fact that helicopters spend a very significant fraction of their flying time in a region of the atmosphere where temperature and water content are likely to lead to hazardous conditions;

(c) the fact that compared with fixed wing aircraft the lifting surfaces on a helicopter are expected to function across a much broader spectrum of aerodynamic conditions (e.g. airspeed and angle of attack). These create at one extreme the possibility of a high rate and efficiency of water catch per unit chord distance and, at the other, a 'close to stall' state. The complexity of rotor support and control gear also make it difficult, expensive and likely to create significant weight penalties, to provide anti-icing or de-icing facilities. The helicopter is an intrinsically vulnerable aircraft which it is difficult to protect by conventional means;

(d) the fact that helicopters can, and occasionally must, remain in a rather closely defined geographic location. In doing so, they become sensitive to a scale of atmospheric inhomogenity which has not received the same attention as the synoptic scale for example and which is certainly very difficult, if not impossible to forecast.

5. The role of the meteorologist

The designer of helicopters, and those creating protection systems and assessing their ensuing operational role, are concerned to know the probability of a particular hazard being experienced at a given place and time. Thus a typical hazard might be an unacceptable increase in the torque necessary to achieve a required lift on a Sea King helicopter, in the vicinity of say 60°N, 0°W, in January. The probability of this occurring must itself be the product of the probability that the hazard will result from particular meteorological conditions and the probability that such conditions will exist at the required position and time. The problem of defining these probabilities contains meteorological and engineering components, which are intimately connected. The meteorologist may reasonably expect that the atmospheric parameters whose climatology is required be clearly specified. The engineer may reasonably expect that those parameters which are likely to be experienced be identified so that he may determine their icing effect.

The meteorologist, with some justification, will argue that the broad envelope of conditions which are likely to create hazards can be (indeed have been) identified. However, the difficulty of discovering the actual physical basis of the creation of icing hazards continually creates pressure for refinement of this envelope. There is little doubt that some refinement is possible, perhaps not through the provision of more detailed statistics, but by applying accepted physical understanding to the problem. Hence the first role of the atmospheric physicist is likely to be interpretative. A few examples serve to illustrate the approach:

(1) In section 2, the thermal importance of mixtures of ice and water was identified. However, thermally significant mixtures may have a very limited, transient occurrence in the real atmosphere because of the supersaturation experienced by ice particles in the presence of water drops below 0 °C.

Quantitative arguments of this type are unlikely to demonstrate that all atmospheric occurrences of ice and liquid water have a low probability (snow falling through supercooled cloud may not be in equilibrium, for example). However, the potential simplification certainly justifies a numerical study of the problem.

(2) Calculations of the maximum free water content of ascending air (see Ludlam (1957) for example) together with a crude climatology of surface temperature, could be used to create a useful upper bound for cloud water content. This idea was briefly discussed by Jones (1961) but so far as is known has not been used in the way suggested.

There is a fundamental requirement that progress must be made in understanding the physics of hazard creation. This will not be achieved until instruments are available to observe and quantify the icing process and the co-existing state of the atmosphere. The atmospheric physicist may reasonably expect to contribute to this required development. Recent improvements in drop sizing instrumentation (Knollenberg, 1976 are likely to assist here.

It may reasonably be argued that any attempts to define a climatology of icing parameters more closely must await their full recognition. For example, it may be that drops of diameter greater than say 25 μm play a crucial role in rotor blade icing because of the much reduced collection efficiency experienced by smaller sizes. If this supposition was in fact found to be correct, it would certainly have a significant effect on a study aimed at defining the incidence of icing hazards. Nevertheless, although the timing of a study is open to question, there is little doubt that an improved definition of the probability of occurrence of various combinations of atmospheric variables will ultimately be necessary. It has been suggested that if such a study is undertaken more or less in parallel with a properly instrumented study of hazard-creating processes, this will create the most cost-effective solution.

It is important to recognize here that the climatology of interest is unlikely to be of the commonly measured meteorological variables alone. At first sight the task of defining the climatology of, say, liquid water content as a function of temperature, altitude, geographical position and time of year is a horrendous, if not impossible one. Almost certainly an approach which seeks to separate the problem into climatological and interpretative components will be necessary. Thus, it is suggested that existing synoptic data be used to define the probability of occurrence of, for example, cloud type and amount, cloud base height, and surface temperature over the region of interest and that the relationship between these and icing parameters be established separately. An understanding of the physics of water substance in the atmosphere will be an essential ingredient in such a solution, of course, but there is no doubt that currently available atmospheric data are inadequate to meet the latter task. The source of the information required is expected to be a mixture of existing data, new measurements obtained on a dedicated and properly instrumented aircraft such as the MRF C-130, and measurements obtained through the use of precipitation radar and satellite imagery.

Any attempt to improve forecasting techniques must be preceded by a clearer understanding of present deficiencies and the nature of realistic future improvements. There is little doubt that attempts to improve synoptic scale temperature and atmospheric water content predictions could be made but whether or not this would fill a real need is far from clear. As with the atmospheric study program described above, perhaps the greatest single contribution that the meteorologist can make to the problem is that of helping to formulate the questions as well as the answers.

REFERENCES

BEST, A. C. 1956 Ice accretion on aircraft in warm-front conditions. *Met Mag*, **85**, pp. 257–263.

BRUN, E. A. 1957 Icing problems and recommended solutions. North Atlantic Treaty Organization, Advisory Group for Aeronautical Research and Development. *AGARDograph* No. 16.

CANSDALE, J. T. and MCNAUGHTAN, I. I. 1977 Calculation of surface temperature and ice accretion rate in a mixed water droplet/ice crystal cloud. Farnborough, Royal Aircraft Establishment. *Technical Report* 77090.

HARDY, J. K. 1946 Protection of aircraft against ice. Farnborough, Royal Aircraft Establishment. *Report* No. S.M.E. 3380.

JONES, R. F. 1961 Ice formation on aircraft. Geneva, World Meteorological Organization. *Technical Note* No. 39.

KNOLLENBERG, R. G. 1976 Three new instruments for cloud physics measurements: the 2-D spectrometer, the forward scattering spectrometer probe, and the active scattering aerosol spectrometer. Boston, Mass., American Meteorological Society. *International Cloud Physics Conference, July 1976, Boulder, Colorado*, pp. 554–561.

LANGMUIR, I. and BLODGETT, K. B. 1946 A mathematical investigation of water droplet trajectories. Wright Field, Dayton (Ohio), U.S.A.A.F. Air Materiel Command, *A.A.F. Technical Report* 5418.

LUDLAM, F. H. 1957 Introduction to the first edition of 'The physics of clouds' by B. J. Mason (London, Oxford University Press).

MESSINGER, B. L. 1953 Equilibrium temperature of an unheated surface as a function of airspeed. *J Aero Sci*, **20**, pp. 29–42.

APPENDIX

c_p = specific heat of air at constant pressure $= 1005$ J kg^{-1} K^{-1}
c_w = specific heat of water $\approx 4{\cdot}2 \times 10^3$ J kg^{-1} K^{-1}
E = particle collection efficiency
E_c = particle collision efficiency
E_a = accretion efficiency
D = cylinder diameter
e_{sw} = vapour pressure over water at t_s
e_{si} = vapour pressure over ice at t_s
e_∞ = vapour pressure of free atmosphere
h = convective heat transfer coefficient
k_a = thermal conductivity of air $\approx 2{\cdot}4 \times 10^{-2}$ W m^{-1} K^{-1}
L_e = latent heat of evaporation $\approx 2{\cdot}5 \times 10^6$ J kg^{-1}
L_f = latent heat of fusion $\approx 3{\cdot}3 \times 10^5$ J kg^{-1}
L_s = latent heat of sublimation $\approx 2{\cdot}8 \times 10^6$ J kg^{-1}
Nu = Nusselt number $= hD/k_a$
P_∞ = free atmosphere pressure
q = rate of heat transfer per unit area
r = recovery factor
Re = Reynolds number $= \dfrac{\rho_a V_\infty D}{\mu_a}$
R_w = rate of water mass caught per unit area
R_w' = rate of water mass impinging per unit area
t_s = icing surface temperature
t_∞ = free atmosphere temperature
V_∞ = free atmosphere velocity
W = mass concentration of water in the air
μ_a = viscosity of air $\approx 1{\cdot}7 \times 10^{-5}$ kg m^{-1} s^{-1}
ρ_a = density of air $\approx 1{\cdot}2$ kg m^{-3}

An approximate value of h is obtained by assuming with Hardy (1946) that at stagnation the Nusselt number and the Reynolds number are related by

$$Nu = (Re)^{\frac{1}{2}}$$

hence

$$h = k_a\left(\frac{V_\infty \rho_a}{D \mu_a}\right)^{\frac{1}{2}}.$$

For the purpose of the budget calculations carried out in section 2, it is assumed that this stagnation value is representative of the whole body.

For $V_\infty = 100$ m s^{-1}, $\rho_a = 1{\cdot}2$ kg m^{-3}, $D = 10$ cm, $\mu_a = 1{\cdot}7 \times 10^{-5}$ kg m^{-1} s^{-1}, and $k_a = 2{\cdot}4 \times 10^{-2}$ W m^{-1} K^{-1} i.e. representative of surface air at ≈ 0 °C, $h = 200$ W m^{-2} K^{-1}.

The so-called recovery factor, representing the influence of a cylinder on free stream values of V_∞ for example, has been assumed to be $\approx 0{\cdot}9$ for budgetary purposes.

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THE 'EXPLORATION' EXHIBITION AT THE SCIENCE MUSEUM

'Exploring Our Changing Climate' by Tom Williamson (HMSO, 1977)

By R. P. W. LEWIS
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On 16 December 1977 a new major exhibition based on the theme of 'Exploration' opened at the Science Museum in South Kensington; it is expected to run for at least three years. There are six sections: Remote Sensing, Medical Science, Underwater Exploration, Man on the Moon, The Planets and Beyond, and—of most immediate professional interest to meteorologists—Our Changing Climate. The standard of presentation is of the usual high metropolitan quality with superbly arranged exhibits and show-cases, working models and demonstrations, audio-visual displays, and apparatus and instruments (for example the

Apollo 10 Spacecraft) that have actually been used in many of the investigations described. The booklet by Tom Williamson, a member of the Science Museum staff, is one of six published simultaneously in connection with the exhibition which are on sale in the Museum; it is excellently produced, with text and pictures—many of which are in colour—skilfully blended together. (The Meteorological Office has not been involved with either the exhibition or the booklet.)

The booklet gives what is on the whole a reasonably fair presentation of what is now known, or at least suspected, to be the way in which 'climate' has changed in the past and may possibly change in the future. It is, however, remarkable that nowhere is any attempt made to define or even to explain the terms 'climate' or 'climate change', or to distinguish the latter from ordinary year-to-year fluctuations. All the evidence for climatic change in the remote past—and indeed much in the comparatively recent past—is indirect and derived from geological and biological observations such as lake levels, the thicknesses of varves, concentration of fossil pollen-types and so on. The rates of growth and deposition, or indeed the very existence, of different living species will depend on different combinations of factors only some of which are meteorological, and the meteorological factors are themselves likely to be different for each species. Possible examples are maximum temperatures at certain seasons of the year, threshold values of rainfall or humidity, and mean annual and seasonal mean values of temperature, rainfall and sunshine; the periods over which such critical values are significant will also be different for each species and will be related to the life and reproductive cycle of that species. Furthermore, biological evolution will have taken place on the longer time-scales leading to alterations in response. It is thus obvious that 'climate change' as represented by the record of abundance of one species, or by the structure of the rings from one tree, will be different—perhaps very different—from that represented by records from another species, and neither may bear any obvious relation to changes in a simple 30- or 100-year mean of temperature. As a leading agricultural meteorologist remarked during a recent meeting of the Royal Meteorological Society, even when we know actual values of temperature, rainfall and sunshine, it is difficult if not impossible to predict the growth of a plant to any high degree of accuracy, so that to attempt to reverse the process is even more speculative. Much work is of course being done to refine the various 'proxy-data' methods, but visitors to the exhibition are not made sufficiently aware of the uncertainties of current knowledge. For example, one exhibit, and one section of the booklet, deal with the alleged evidence for climatic fluctuations in England of the growth and decline of viticulture since the time of the Romans (who introduced the vine). This topic is discussed by Barty-King (1977) who is of the opinion that social and economic factors were of much greater importance than the suggested variations in climate, and that evidence for the latter is negligible.

Prominence is given to oxygen isotope analysis as applied to the annual layers of wood in trees, ice-cores from Greenland and the Antarctic, and cores of deep-sea sediment. However, just because something is measured to a very high degree of precision by means of advanced laboratory techniques, it does not follow that deductions made from the measurements are equally precise or even valid; unless the assumptions in the chain of reasoning are fully explained, and the weak links discussed, then the ignorant visitor is merely being 'blinded by science'.

(The empirical evidence for relating fluctuations in ^{18}O concentration to a plausible measure of climate such as a long-period mean of surface or tropospheric temperature is not very extensive and shows substantial scatter. Thermodynamical arguments applied to the formation of liquid water in rain cannot be made precisely quantitative because of the complexity of, and essential lack of equilibrium in, the processes involved.)

One of the more impressive exhibits demonstrates the effect of fluctuations in the parameters of the earth's orbit round the Sun on the distribution in space and time of solar radiation incident on the earth; these parameters comprise eccentricity, longitude of perihelion, and obliquity of the axis of rotation. The relationship of these fluctuations to the Milankovitch theory of climatic change is clearly explained. This theory is, however, described in the booklet as 'now . . . firmly established as the main reason for the comings and goings of the ice during the last 3,000,000 years' in the light of the paper published in *Science* by Hays *et alii* (1976). A caption to one of the exhibits states 'Recent studies of heavy oxygen in shells from the ocean floor have substantiated the Milankovitch theory of climatic change'. This paper does indeed adduce new evidence in favour of the Milankovitch theory (at least for the last 500 000 years!) but to describe the theory as 'firmly established' rather overstates the case. Proxy-data such as those considered by Hays *et alii* require rather involved treatment to convert them into a temperature record, and there are bound to be uncertainties of unknown magnitude in the estimated temperature fluctuations and—more important—in the regularity of the time-scale for which assumptions about the rate of deposition of deep-sea sediments have to be made. The statistical methods employed by the authors are also open to criticism (Evans and Freeland, 1977; Ross, 1978).

Most of the captions to the displays in the exhibition are taken from the booklet. Sometimes they have been taken out of context and, deprived of some of the explanations and qualifications surrounding them, are made to appear unduly sensational. An example is to be found in the announcement in very large letters over the entrance: 'The long-term future of our climate can now be predicted. It is a bleak one'.

The list of titles for 'further reading' at the end of the booklet could be improved. Books of dubious scientific value such as 'The Weather Machine' by Nigel Calder are recommended as well as what is probably the best available recent review of the subject, viz. 'Understanding Climatic Change—a Program of Action' published by the US National Academy of Sciences.

Nature and *New Scientist* are recommended as containing articles of technical interest, but no mention is made of any journal specializing in meteorology or climatology. The Symons Memorial Lecture by Mason (1976) could also well have been alluded to.

REFERENCES

BARTY-KING, H.	1977	A tradition of English wine. Oxford, Oxford Illustrated Press.
EVANS, D. L. and FREELAND, H. J.	1977	Variations in the Earth's orbit: Parameter of the Ice Ages? *Science*, **198**, pp. 528–529.
HAYS, J. D., IMBRIE, J. and SHACKLETON, N. J.	1976	Variations in the Earth's orbit: Parameter of the Ice Ages. *Science*, **194**, pp. 1121–1132.
MASON, B. J.	1976	Towards the understanding and prediction of climatic variations. *Q J R Met Soc*, **102**, pp. 473–498.
ROSS, G. H.	1978	Comments on 'Variations in the Earth's orbit' by Hays *et alii*. Unpublished typescript, Meteorological Office, Bracknell.

REVIEWS

Introduction to the mathematics of inversion in remote sensing and indirect measurements, by S. Twomey. 245 mm × 165 mm, pp. x + 243, *illus.* Elsevier Scientific Publishing Company, Amsterdam, 1977. Price: US $65.

The technique of remote sensing is becoming increasingly important throughout science and particularly in meteorology, owing to the great improvement in the volume and geographical coverage of data provided by weather satellites. These measure the radiation emitted by the earth in narrow spectral bands, and the recovery of information on the vertical profiles of temperature, humidity, liquid water content etc. is achieved through the mathematical process of inversion. Until the advent of the high-speed computer, numerical solutions to many inversion problems proved intractable, and although the underlying algebra was understood, the difficulties associated with obtaining a numerical solution were not fully appreciated. Recently, however, numerical inversion methods have received a great deal of attention, and have been used operationally to produce, for example, vertical temperature soundings of the atmosphere.

In this book the author examines the mathematics of inversion methods in detail, starting from basic principles, and discusses various mathematical topics which are fundamental to the inversion problem.

He begins by describing the inversion problem and shows that many varied physical processes fall within the framework of the mathematics of inversion. Some mathematical topics which are essential for an understanding of inversion are then introduced. These topics include matrix algebra, quadrature techniques, eigenvalues and eigenvectors, the concepts of orthogonality and norms, and geometical aspects of functions and matrices.

The inversion problem itself is next examined, with the author illustrating its inherent instability. This instability arises since, in the presence of measurement errors, measured functions differing only slightly from one another could have been produced by source functions differing vastly from one another. It is shown that this instability is inherent in the problem itself and is not a consequence of approximating the integral equations which are typically encountered in inversion problems by means of quadrature formulae, and is not a consequence of computer round-off during the calculation. The author shows how the application of suitable constraints on the solution can combat the instability, giving advice on how to choose appropriate constraints and how to apply them to the inversion procedure. These constraints are of course external to the problem and so it is shown how the production of a reasonable solution depends to some extent on the constraints chosen. Finally the topics of error analysis and the information content of indirect sensing measurements are discussed, and their relationship with the inversion problems examined.

This book succeeds in filling a gap in the literature since most material published on the subject tends to be rather specialized in its application, while Twomey has gathered material which was previously scattered throughout many fields. The book has been aimed primarily at students on courses on remote sensing and satellite studies, although the research worker should also find it instructive. It should help him to see his problem in the context of the underlying mathematics, and remind him of the instability of the basic problem and the arbitrariness of the constraints he employs to overcome it.

My one small criticism of the book is that I would like to have seen at least one actual physical problem examined in detail numerically, perhaps in an appendix. The author does use a simple retrieval problem to illustrate the efficacy of different retrieval methods and the effect of the constraints employed, and while the example used is illustrative, it might nevertheless have been instructive to have seen a real problem tackled somewhere in the book.

To conclude, I found this book very readable and thoughtfully set out, and found it useful since it brings together the many aspects of inversion mathematics necessary for a more complete understanding of the techniques of remote sensing, although at a price of $65, readers may wish to obtain their copy from a library.

J. S. CAMPBELL

Climates of central and southern Europe, World Survey of Climatology, Volume 6, edited by C. C. Wallén. 300 mm × 210 mm, pp. ix + 248, *illus.* Elsevier Scientific Publishing Company, Amsterdam, 1977. Price: US $67.50.

The climates of four regions of central and southern Europe are described by different authors, but with a common method of presentation.

Chapter 2, on central Europe, including Germany, Austria and Switzerland, begins with an excellent account of the general geographical and climatological features, and then discusses the general circulation in broad terms, but makes clear the characteristics of severe winters such as those of 1928/29, 1941/42 and 1962/63, and, while pointing out that the area receives its main precipitation in summertime, describes how the north-eastward advance of the Azores high may cover central Europe for long spells in the summer, as in 1904, 1911, 1921, 1947, 1959, 1964 and 1971. The annual variation of atmospheric conditions is discussed in terms of the large-scale extended weather types (Grosswetterlagen) as defined by Hess and Brezowsky. A broad seasonal picture is given, followed by monthly characteristics, in which the important synoptic types are described with great clarity, for example the mild westerly types and cold easterly types of winter, and the violent northerly winter storms of the North Sea. The contrasting spring types of southerly föhn and arctic northerlies bringing severe frosts to the northern slopes of the Alps are described with examples and statistics of occurrence. Brief but clear accounts of the early summer monsoon and the predominant thundery col situations of high summer are given. The distinction between the winter and early autumn high-pressure situations is well drawn; the winter type is often meridional, while the autumn type is more zonal with weaker pressure gradients over the area, giving warm sunny days with early morning fog. The great variations in central Europe of continentality and topography, from the northern lowlands to the central highlands and then the Alps, have important influences on the seasonal weather types and these are well described. Maps of the climatic elements are accompanied by a brief text, and the chapter closes with a good list of references and 26 climatic tables. The chapter gives a good brief account of the synoptic climatology of central Europe.

Chapter 3 describes the climate of Poland, Czechoslovakia and Hungary. A classification of circulation types is given, and some examples of weather types, but no clear picture of the synoptic climatology emerges, and even the section on the spatial distribution and annual pattern of the meteorological elements is not very informative.

Chapter 4 on the climate of Italy has a concise account of geographical influences on the climate of the peninsula, emphasizing the barrier effects of the Alpine–Apennine range, and the influence of the Mediterranean, but no synoptic examples are given, even of mistral or bora conditions, although the passage of a winter cold front is illustrated by three-hourly isochrones. The main cyclogenetic areas of the Mediterranean in winter and summer are mapped out, and related to 700 millibar weather types, but without synoptic examples. A brief account is given of variations in the main Italian climatic regions. Mapping of climatic elements is useful, with great detail on thunderstorm and fog frequencies.

Chapter 5 on the climate of south-east Europe consists almost entirely of a description of the main characteristics of the most important climatic elements, emphasizing the effects of the great meridional extent of the area, and those of topography and continentality. It provides little or no information on the synoptic climatology of the region.

The claim on the jacket of the volume that 'all chapters give a review of the atmospheric circulation and its synoptic features' is very inadequately substantiated, and the further claim that 'this book will be of great value in teaching regional European climatology at university level' seems unjustified.

A. F. JENKINSON

Exploring our changing climate, by Tom Williamson. 220 mm × 195 mm, pp. 28, *illus.* London, Her Majesty's Stationery Office, 1977. Price: 75p.

A review of this publication is included in the article by R. P. W. Lewis which appears on pages 147–149 of this issue of the *Meteorological Magazine.*

OFFICIAL PUBLICATIONS

The following publications have recently been issued:

Maps of average annual rainfall over the United Kingdom

Maps of average annual rainfall over the United Kingdom for the international standard period 1941–70 are now available. Rainfall is shown by black isohyets overprinted on an Ordnance Survey 1 : 625 000 map (approx. 10 miles = 1 inch) showing ochre-shaded topography, place names, roads, rivers, and the National Grid.

They are in three parts:

North Britain —England north of a line Seascale (Cumbria) to Ravenscar (North Yorkshire), and Scotland, including the Hebrides, Orkney, and Shetland.
80 × 100 cm. Met. 0.886(NB). £1.00 (plus postage and packing.)

South Britain —England south of a line Seascale (Cumbria) to Ravenscar (North Yorkshire), with an inset showing the Channel Isles.
80 × 100 cm. Met. 0.886(SB). £1.00 (plus postage and packing.)

North of Ireland—Northern Ireland together with adjacent counties of the Republic of Ireland.
30 × 44 cm. Met.0.886(NI). 75p (plus postage and packing.)

Enquiries should be made to Meteorological Office Met O 8c (Room 227), London Road, Bracknell, Berkshire RG12 2SZ, *or* The Superintendent, Meteorological Office, 231 Corstorphine Road, Edinburgh EH12 7BB, *or* The Principal Meteorological Officer (Northern Ireland), Tyrone House, Ormeau Avenue, Belfast BT2 8HH. Weather Centres at Glasgow, Newcastle, Manchester, Nottingham, London, and Southampton have stocks for sale across the counter but they cannot deal with mail order requests. These maps cannot be obtained from Government Bookshops.

NOTES AND NEWS

Changes in senior appointments within the Meteorological Office

The following changes in senior appointments have recently been announced:

Mr F. H. Bushby on promotion to Under Secretary will become the Director of Services of the Meteorological Office on 2 May 1978 following the retirement of Mr G. A. Corby.

Mr D. H. Johnson on promotion to Deputy Chief Scientific Officer will become Deputy Director (Forecasting) on 2 May 1978 in succession to Mr Bushby.

Mr R. J. Ogden will become Assistant Director (Public Services) on 2 May 1978 in succession to Mr Johnson.

Mr C. R. Flood on promotion to Senior Principal Scientific Officer will become Assistant Director (Climatological Services) on 2 May 1978 in succession to Mr Ogden.

Dr R. L. Wiley on promotion to Senior Principal Scientific Officer will become Assistant Director (Systems Development) on 6 June following the retirement of Mr E. J. Sumner.

Aerobiology: a new Assembly of Life Sciences Program

From time to time, the Assembly of Life Sciences* assesses the health of a discipline under its purview through a symposium, study committee, or other device. Aerobiology, a field of study that is engaging the attention of an increasing number of scientists, is the most recent example. From 1967 to 1974, aerobiology was a component of the U.S. International Biological Program (IBP). A major goal of that effort was to develop a basis for international co-operation in mitigating the consequences of atmospheric transport of pathogens, pests, and toxic materials. Among the disciplines involved were meteorology, plant pathology, entomology, allergology, medical mycology, and palynology.

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* Assembly of Life Sciences, National Research Council, National Academy of Sciences, 2101 Constitution Avenue, NW, Washington, DC 20418, USA.

As a direct consequence, an International Association for Aerobiology was established. This is now recognized as a Commission of the Division of Environmental Biology in the U.S. National Committee for the International Union of Biological Sciences (USNC/IUBS).

In a related move, several scientists associated with the IBP's Aerobiology Program urged the establishment of a Committee on Aerobiology in the Assembly of Life Sciences to see what might be done to further the maturation of aerobiology as a discrete, coherent science and to assist, if judged timely, in launching an American professional society for aerobiology. Other essential tasks of the committee would be to define clearly the limits of aerobiology as a discipline, to characterize its key problems, and to determine how these problems are being met by the various federal agencies. The committee has been appointed and hopes to achieve its primary objectives within three years, after which it will either be phased out or continue as a small subcommittee of the USNC/IUBS to handle international obligations.

Important areas of committee concern include:

Pollen and spore distribution. The results of sampling in a number of sites around the world are tabulated and published annually in the *Statistical Report of the Pollen and Mold Committee of the American Academy of Allergy.* Data on the non-pathogenic species are less readily available. The role of air currents and insects in the transport of pollen throughout the various ecosystems has received scant attention. Rural assemblages of airborne species are very different from those in urban ecosystems and little attention has been paid to airborne plant and animal material in the indoor environment.

Phytopathogens. It is important to ascertain as precisely as possible the exact time that spores or vectors arrive at crop foliage. This would ensure the timely application of pesticides. Air sampling and uniform data formats should enable scientists to forecast the inflow of plant pathogens before disease reaches epidemic proportions.

Microfauna, including insects. Monitoring the movements of insect vectors is important to the health and well-being of humans and animals. Many insects are vectors of plant pathogens. Some species, such as aphids, are carried long distances; others such as leaf-hoppers, mosquitos, house-flies, and moths, are restricted by many factors, including natural barriers and weather conditions. Proper sampling is a very important aspect of dispersion studies. The most effective devices for sampling such delicate organisms as algae and protozoa are bubblers, membrane filters, and exposed culture plates. Little is known of the source of algae in the atmosphere, and no studies have been designed to correlate airborne algae and protozoa with the biota of a given area.

Health of humans and animals. Certain components of the atmosphere directly affect the health of humans and animals, particularly in the areas of allergy and infectious disease. The physical characteristics that endow pollen grains and fungal spores with the capacity for airborne movement are equally responsible for their ability to affect the respiratory tract. Special environmental circumstances can lead to skin eruptions and to hypersensitivity pneumonias in certain occupational groups. Air conditioning and humidification systems have added a new dimension to indoor exposure to airborne allergens.

The peculiar environmental and atmospheric conditions favourable for propagation of specific fungal pathogens (e.g. Coccidioides, Histoplasma) have long been recognized. The potential for airborne spread of other types of micro-organisms, usually considered contagious only by close contact, is less recognized. There are documented instances when diseases caused by bacteria (anthrax), rickettsia (Q fever), and viruses (foot-and-mouth disease) have spread because of critical meteorological conditions or aerosolization.

Effects of pollutants. Although air pollutants are best known for their direct effect, photochemical oxidants, especially ozone and sulphur dioxide, can inhibit the germination of certain fungus spores and pollens; pollutant gases variously affect the viability of airborne fungus spores and bacteria.

Meteorology. Meteorology is pivotal to aerobiology as it relates to atmospheric transport. Many factors that control the movement of biological materials can be examined by essentially the same physical techniques as can non-living phenomena. Observation (monitoring), quantitative evaluation, and forecasting of these processes are of critical importance to aerobiologists. Certain specialized release mechanisms, the attribute of flight, and the complex aerodynamics of many biological components add extra dimensions to the problem. Intramural transport of bacteria and allergens reflect certain meteorological characteristics of diffusion and turbulence.

Biological particles can also act as nuclei for cloud condensation and for ice formation, can serve as centres of coalescence, and can supply surface-active agents. These roles of the aerobiota are yet poorly understood, but the potential has been clearly demonstrated.

The committee is chaired by Dr Robert L. Edmonds, Director of College Lands, College of Forest Resources, University of Washington. Other members are Drs Donald Aylor, Department of Ecology and Climatology, Connecticut Agricultural Experiment Station; Sheldon G. Cohen, Natural Institute of Allergy and Infectious Diseases; Bruce F. Eldridge, Department of Entomology, Walter Reed Institute of Research; Russell C. Schnell, Mount Kenya Study, U.S. Development Program, Nairobi; Gabor Vali, Department of Atmospheric Resources, University of Wyoming; and Jack R. Wallin, Department of Plant Pathology, University of Missouri.

HARVEY E. SHEPPARD
Staff Officer
Committee on Aerobiology

OBITUARY

We record with regret the death on 8 December 1977 of Mr J. A. Flawn, Senior Scientific Officer, as a result of the tragic aircraft accident at RAF Akrotiri, Cyprus. Jack Flawn joined the RAF Met. Branch in June 1942 and had a variety of war-time postings, at Army establishments at home, and with the Royal Air Force in the Mediterranean and Middle Eastern areas overseas. After demobilization in 1946 he served in all regions of the United Kingdom, mainly at outstations, with a spell of nearly 15 years at Aberporth from 1961 to 1976. He was detached from Aberporth for a time in 1974 to help with the international Atlantic tropical experiment (GATE) and took charge of observations on the *Endurer*, one of the two ships supplied for GATE by the United Kingdom. In 1976 he was posted to Akrotiri. He was a keen and experienced sailor and while in Cyprus he was an active member of the Near East Off-shore Cruising Club.

CORRECTIONS

Meteorological Magazine, April 1977

	As printed	Corrected value
Page 105, Table VI		
1823	93.8	107.0
Pages 106–110, Table VI		
February 1727	204	264
February 1752	144	143
May 1752	222	221
Annual total 1752	2202	2200
Annual total 1760	1900	1902
December 1766	186	185
November 1781	329	239
Annual total 1811	2576	2578
Annual total 1823	2220	2630
Decadal average 1821–30	2688	2719
July 1831	499	490
August 1911	140	146
May 1924	374	324

THE METEOROLOGICAL MAGAZINE

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CONTENTS

NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, and marked 'For Meteorological Magazine'.

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

Complete volumes of 'Meteorological Magazine' beginning with Volume 54 are now available in microfilm form from University Microfilms International, 18 Bedford Row, London WC1R 4EJ, England.

Full size reprints of out-of-print issues are obtainable from Johnson Reprint Co. Ltd, 24–28 Oval Road, London NW1 7DX, England.

Issues in Microfiche starting with Volume 58 may be obtained from Johnson Associates Inc., P.O. Box 1017, Greenwich, Conn. 06830, U.S.A.

Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1 monthly **Annual subscription £13.14 including postage**

Dd. 595890 K15 5/78

ISBN 0 11 724799 5
ISSN 0026–1149

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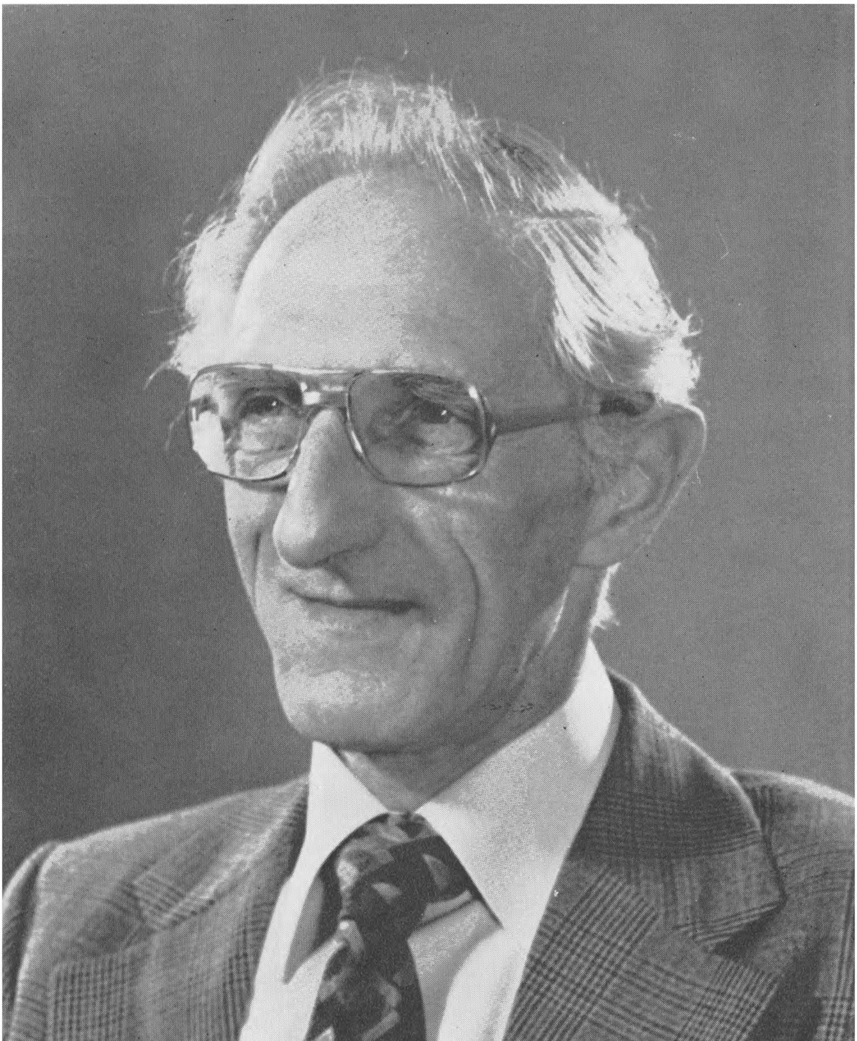
METEOROLOGICAL OFFICE

the meteorological magazine

JUNE 1978 No 1271 Vol 107
Her Majesty's Stationery Office



Photograph by G. A. Corby

MR G. A. CORBY

METEOROLOGICAL OFFICE Met.O.915

THE METEOROLOGICAL MAGAZINE

No. 1271, June 1978, Vol. 107

RETIREMENT OF MR G. A. CORBY

On the retirement of Mr G. A. Corby as Director of Services on 30 April 1978, the Meteorological Office lost one of the most able, versatile, popular and respected figures of the post-war era. In an outstanding career spanning 37 years, during which he achieved a high reputation as a forecaster, research scientist and senior administrator, he brought a high degree of dedication, professional ability, excellent judgement and a sense of style to every task. His contribution and influence have been immense.

Educated at St Marylebone Grammar School and London University, he graduated with first class honours in mathematics in 1941 and entered the Office in September of the same year. After joining the RAFVR Meteorological Branch in April 1943, he served in India, Ceylon and Singapore until the end of the war. After demobilization in July 1946, he spent a short time at London Airport as a forecaster and then took charge of the office at Northolt where he was promoted to Principal Scientific Officer in 1949. In October 1953 he joined the newly formed Forecasting Research Branch at Dunstable where he made his mark as a research scientist in a series of important papers on the airflow over mountains and atmospheric waves and carried out one of the first experiments in three-dimensional objective analysis. These contributions were recognized by the award of the L. G. Groves Memorial Prize in 1954.

In 1963 he was promoted to Assistant Director to establish a new research branch in Dynamical Climatology where he was the architect of the very successful 5-level global circulation model and led the team which developed the powerful 13-level model that produced a very realistic sudden stratospheric warming on its first long-period integration. It was during this period that George Corby demonstrated his scientific leadership and his talents as a mathematician with a deep knowledge and understanding of dynamical meteorology. One cannot but wish that he could have started his research career much earlier and received greater recognition of his own scientific talents.

However, his abilities were well appreciated within the Office where he was promoted to Deputy Director in charge of computing and telecommunication services in 1973 in preparation for his final promotion to Director of Services and deputy to the Director-General, with the rank of Assistant Under Secretary, in 1976.

In this demanding role he has been a tower of strength, dealing with a whole range of important issues with cool, calm and excellent judgement and with the complete co-operation and confidence of his staff.

I shall miss his wise and courteous counsel and unfailing support. I am sure that all George's friends and colleagues will join me in wishing him and Mrs Corby a long and happy retirement with more time for his other interests of music, photography and cabinet-making to which he brings the same degree of skill and professionalism that has characterized his work in meteorology.

B. J. MASON

METEOSAT

Meteosat, which is the geostationary meteorological satellite of the European meteorological community, together with the associated program of data collection and dissemination, will form one of the most important European contributions to the First GARP Global Experiment (FGGE). Meteosat, which was developed by the European Space Agency, was successfully launched on 23 November 1977 from Eastern Test Range, Florida by NASA, using a Delta 2914 vehicle. Test transmissions producing excellent pictures began shortly afterwards.

Meteosat is a geostationary satellite, that is to say it travels round the centre of the earth in a circular orbit in the equatorial plane with the same angular velocity as the earth, so that it remains stationary relative to points on the earth's surface; it lies at a height of about 36 000 km over the Greenwich meridian. When it becomes fully operational it is hoped that it will produce images every 30 minutes in one band of the visible spectrum (0·4–1·1 μm), and two bands of the infra-red spectrum (5·7–7·1 μm for water vapour and 10·5–12·5 μm for thermal emissions). The resolution at the subsatellite point is 2·5 km for the visible image and 5 km for the infra-red. Meteosat spins about its axis at 100 r/min and this spin is made use of in the optical arrangements for systematically scanning the earth's surface. The focused visible and infra-red signals are converted into analogue electrical signals by various detectors, processed, and transmitted to the central ground station near Darmstadt (Federal Republic of Germany). Following certain further processing of the data received at Darmstadt, images are disseminated via the spacecraft to user stations operated by various meteorological services (for example Lasham in Hampshire for the Meteorological Office) and eventually quantitative products (e.g. winds) will be distributed over the normal meteorological telecommunication channels.

(See Plates I–III.)

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THE SIGNIFICANCE OF METEOSAT FOR METEOROLOGY*

By K. H. STEWART

(Director of Research, Meteorological Office, Bracknell)

The paper that follows was written in response to a request from the European Space Agency for an article for a special issue of their *Bulletin* designed to celebrate the launch of Meteosat. It seemed appropriate to deal with the meteorology in a simple way and to put emphasis on the benefits to be expected from Meteosat; I hope readers of the *Meteorological Magazine* will not feel I have simplified things too much or taken an unreasonably optimistic view.

Meteorology is both a pure and an applied science. As pure scientists meteorologists try to understand and explain the phenomena of weather and climate. As applied scientists they use their knowledge to give advice on the effects of weather on agriculture, industry, transport and daily life. The main practical demand is for forecasts of what the weather will be like in the future—from a few hours ahead to many centuries ahead—but information on past and present weather and its effects can be very important too. Observations provide the essential foundation for both the understanding and the prediction of weather, and the appetite of meteorologists for observations is almost insatiable. Ideally, the observations should measure the state of the atmosphere—its composition, temperature, pressure and velocity—at all heights all over the globe. The space and time resolution required depend on the phenomenon being studied and are closely linked together, because small-scale phenomena tend to have short life-cycles, and large ones long ones. Local weather forecasts for a few hours ahead require a resolution of a few kilometres in the horizontal and less than an hour in time. Forecasts for a few days ahead require a horizontal resolution of a few hundred kilometres and time-resolution better than a day. For purposes of pure science it might be enough to collect such observations for a limited period only, long enough to obtain a sample of all the important phenomena of meteorology. For the applied science of forecasting, however, there is no limit to the time for which observations are required. This is because we are trying to predict the behaviour of an inherently unstable system. However well we can predict the future development of the flow patterns existing at one time, there will always be new disturbances to the pattern which grow from below the threshold of detectability and have to be taken into account in making later predictions.

Although meteorologists have always been hungry for observations it is only in the last decade or two, with the development of large computers, that they have had the capacity to digest them in the large quantities they know to be necessary. In the last few years the capacity of computers to model the behaviour of the atmosphere, both globally and on more local scales, has far outstripped the capacity of conventional observing systems to provide data for testing, developing and using the numerical models. The problem is not that conventional methods are in principle incapable of providing the data required; it is simply that the cost of operating the thousands of stations needed (mostly

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* Reprinted from the *ESA Bulletin* No. 11, December 1977.

in the oceans) would be quite prohibitive. It is no wonder, then, that meteorologists are eager to exploit to the full the possibilities of satellites in providing a world-wide observing system at reasonable cost.

Satellites have been used in meteorology for over 15 years. The first glamour and excitement has faded, leaving the conviction that satellites can make an enormous contribution to meteorology but also the realization that it is not a simple matter to make full use of their potential contribution. Satellites do not observe directly the quantities meteorologists most need to know and much ingenuity and effort have to be expended to plan the satellite system to best advantage and to extract the maximum of useful information from its data. The first and strongest reason European meteorologists have for welcoming Meteosat is that it enables them to play a really active part in exploring and extending the ways of using satellites in their science; of course, much work has already been done using data from American satellites, but the full understanding of the limitations and possibilities of satellite techniques that is needed to exploit them fully comes only from working in close and interactive contact with the system and its data. During the development of Meteosat only a rather small circle of meteorologists has benefited from this contact, but the circle has widened as the day of launch approaches and once the data begin to flow in, the challenge and the opportunity will be open to the whole community of European meteorologists.

Meteosat has been planned to complement rather than duplicate existing weather satellites. For many years the USA has provided satellites in fairly low near-polar orbits which give coverage of the whole earth once or twice per day. The observations from these satellites have improved gradually over the years and will take a big step forward in 1978 when the TIROS N series is introduced. The satellites provide images at several different visible and infrared wavelengths and 'soundings' of the vertical distribution of temperature and humidity. The images give valuable data on conditions at the earth's surface—the distribution of snow and ice and of sea-surface temperature—as well as showing the cloud patterns and thus determining in a qualitative way the main features of the weather systems. The sounding data, in principle, give comprehensive quantitative information about the state of the atmosphere. Although it is only the temperature and humidity that are measured, the pressure can be inferred at all levels (provided it is known at one reference level, such as the earth's surface) through the hydrostatic relation and the wind can be inferred through its relationship to pressure gradient. In practice, there are still serious limitations to the accuracy and vertical resolution of the sounding data. Apart from this technical and, we hope, temporary difficulty, the polar satellites fall short of providing comprehensive data in two important respects. The first is that their coverage is only intermittent—twice per day for most places. This means that the satellites do not provide a satisfactory sample of weather observations for long-term studies, because weather in the afternoons, for example, may be systematically different from that in the mornings. It also means that they do not provide adequate data for short-term forecasts; if we are to predict the development and movement of the small-scale phenomena, such as thunderstorms, which often give weather its most dramatic impact, we must have observations at least once an hour. The second, more technical, inadequacy is that the familiar relationship between pressure gradient and wind is too weak near the equator to allow us to infer wind from the temperature-sounding data. Air movements within the tropics play a vital part in the evolution of global weather and we therefore need some other method of measuring wind there.

These two deficiencies of the polar satellite system can largely be made good by the use of geostationary satellites. These can provide quasi-continuous coverage of the whole area within their field of view, which is what is needed for short-range forecasts, and the wind measuring problem can then also be solved by tracking the motion of clouds over an hour or two and assuming that they move with the wind. The method only works, of course, where clouds are present, and care has to be taken to avoid clouds of types which might not move with the wind, but experience has shown that reasonably adequate sets of data can be obtained. Four or five geostationary satellites are needed to cover all longitudes and these are being provided by a natural geographical division of responsibility, with the European Meteosat located at 0° longitude.

Although the system of polar and geostationary satellites can cover the whole earth adequately, there are several important quantities which cannot yet be measured properly by remote sensors on satellites, atmospheric pressure at the surface, rainfall amounts and river flow being the notable examples. It is not very difficult to devise automatic stations to measure these quantities in remote or inaccessible areas, but the transmission of data from them is often difficult or costly and the satellites can play a very useful role as a data link.

As a geostationary satellite in the African–European sector, then, the role of Meteosat is not to supersede other satellites or the existing network of meteorological stations but to complement them so that, if all systems play their part, the Global Observing System will for the first time give to meteorologists a truly world-wide set of the data they need. The contributions of Meteosat may be discussed more specifically under the four headings: short-range local forecasting, global forecasting, climatological studies and research.

Local forecasting

As already stated, the unique contribution of Meteosat to local forecasting is the quasi-continuous coverage it provides. Images of the clouds will be available every half hour. Images by visible light will only be available in daylight hours, of course, but those at infra-red wavelengths (10–12 μm) will be available day and night and are valuable because they indicate the temperature of the cloud tops (or of the sea surface, in clear conditions) as well as showing the distribution of clouds. The vast amount of detail in these images is beyond the power of any central station to analyse in relation to local conditions, so use will be made of Meteosat's capacity to relay information to broadcast the images to local forecasting stations; before doing so the images are put into a readily usable form at the central station by adding latitude–longitude grids and other information. On receipt, the images will be examined by the forecasters; they will look first to see how well the latest images confirm the ideas they have already formed about the development of the weather from other evidence, then for signs of any new or unexpected developments, particularly in areas not well covered by ordinary observations, then in more detail at features of special interest to their own locality—the spread of fog from the sea to land, for example, or the movement of shower clouds. It is in the field of local forecasting that there is probably most to learn, most room for ingenuity and most likelihood of surprises. We know that in some conditions the new information will be of great value; in other conditions it is not yet obvious how the information can be used but we can hope that experience will teach us. One of the most important uses will certainly be in giving warnings of dangerous conditions such as heavy rainfall or floods. Meteosat can help here not only by its images but also by its capacity to act as a data relay for warning messages from ground stations. One powerful technique whose use is being planned in several countries is that of making a succession of images into a motion-picture of the cloud development; this can give an immediate apprehension of features which may not be obvious from a sequence of still pictures. Another technique that will be used is to combine Meteosat images with those obtained from ground-based radars; these will show the actively raining parts of clouds within the general cloud structure.

Global forecasting

The unique contribution of Meteosat to global forecasting (and it must be remembered that if we are to forecast for any one region for more than a few days ahead, the forecast must necessarily consider the globe as a whole) is the provision of information on winds in the tropical belt. This is one of the most exacting applications of satellite data, demanding great precision in finding the position of the clouds (and therefore in finding the position and orientation of the satellite) and following the motion from one image to the next. The necessary data processing will be done at the central station and the results disseminated by the usual meteorological channels. Other important contributions to large-scale forecasting will be the use of the cloud patterns to delineate weather features and the use of the infra-red image channel to give data on sea-surface temperature. In addition to providing images in the visible and infra-red 'windows' at wavelengths of about 0·7 and 11μm, Meteosat will give images at about 6·3μm, a region of emission and absorption by water vapour. This is a new feature, not included in the geostationary satellites of the USA. The 'water vapour' images should give valuable information on the distribution of water vapour in the upper troposphere (6–8 km above the earth) and may also allow winds to be estimated even when no clouds are visible, by tracking invisible clouds of vapour. The analysis of the images to produce simplified maps of the distribution of cloud, water vapour and sea-surface temperature will be carried out at the central station, and the products will be distributed both by land-line and via the satellite itself. The data-relay powers of Meteosat will be brought into play in two ways in the large-scale forecasting field, first by relaying weather information from remote automatic stations (DCPs), for example in Greenland or on ships at sea, secondly by relaying images obtained from the American geostationary satellite GOES 1 and showing conditions in the west Atlantic and Caribbean otherwise invisible from Meteosat.

These contributions from Meteosat will be vital to the sucess of the important international project known as the First GARP Global Experiment. This project has been planned to obtain the maximum possible global coverage of meteorological data during 1979 and to use the data in numerical experiments designed to explore future possibilities and requirements for the prediction of weather. The Experiment leans heavily on satellite data as well as the conventional observing network, but various supplementary 'special observing systems' will be used too.

Climatology

The role of Meteosat in climatological studies will be primarily to provide statistics on cloud coverage within its field of view; most importance is attached to ocean areas where data are scarce. Climate is determined chiefly by the balance between the radiation received from the sun and that re-radiated by the earth. Clouds have a considerable effect on this re-radiated energy and a comprehensive picture of their distribution and its changes will greatly help our understanding of climate. Although much information has already been obtained from polar-orbiting satellites, it is seriously incomplete because the observations are made only at a few, more or less fixed, times a day. The continuous coverage of the geostationary satellite will allow much more satisfactory estimates of true daily averages to be obtained. As well as giving data on the presence or absence of cloud, the central station will process the data to give estimates of the net 'radiation balance' for each area seen from Meteosat. Other climatological uses of Meteosat may well appear in the future; its use to measure snow cover and to estimate aerosol content are possible examples.

Research

The boundary between research and applications in meteorology is not a distinct one; a forecaster may be described as a researcher who is never allowed the time to complete his research. All of the applications of Meteosat data just described have their research aspects too. The most important is probably the contribution Meteosat will make to the data set of the First GARP Global Experiment. The possession, for the first time, of a truly comprehensive set of data on the world's weather will make possible a great variety of research projects on large-scale atmospheric processes, particularly the fundamental processes that transfer energy from low to high latitudes. On a more local scale, Meteosat will be used to clarify the factors governing African weather—those controlling rain in semi-arid regions being particularly important—to study the local storms that affect the Mediterranean region and to investigate the effects of hills and coastlines on cloud development, to name but a few of the possible projects.

No doubt many small research projects will be carried out by using the images received at local forecasting stations, but the major projects will require access to larger amounts of data and it is here that the comprehensive archiving and data processing facilities provided at the central station will be of great value. Most research will probably be done by requesting the appropriate data sets from the archives but for projects requiring access to and manipulation of really large amounts of data it may be possible for the researcher actually to work at the central station, using its computers during the off-peak period.

This article has tried to show how Meteosat fits into the general scheme of observations for meteorology and what the significance of its contribution in various specific fields will be. In the long run, the Meteosat project may be even more important as a prototype of the techniques and organization that will be needed if meteorology is to make full use of modern technology in the future. Meteorology inevitably uses vast amounts of data, and the problems of collecting the data, processing them to reduce their bulk without destroying their value and then distributing them to the point of use are formidable—particularly when it is remembered that they have to be dealt with continuously and in real-time. The Meteosat satellite provides an advanced means of acquiring data but it was early realized that it would lose much of its value unless supported by adequate data-handling facilities. These have been provided and the basic scheme for their use worked out, but the total system—the satellite as an observing platform, the computers on the ground and the satellite as a data relay station—has enormous flexibility and possibilities of development and adaptation to meet new needs or take advantage of unforeseen opportunities. It will be the task of those who use Meteosat to develop its possibilities to the full and to learn from it the lessons that will lead to a still better system in the future. To end on a personal note, the experience I have been privileged to have of the far-sightedness of the original French designers of Meteosat, the skill and professionalism of the European teams that have carried the project forward and the co-operativeness and enthusiasm of the meteorologists who have planned how to use the satellite leave no doubt that the task will be done well.

551.553.8:551.466.3

WINDFIELDS DURING GALES IN THE NORTH SEA AND THE GALES OF 3 JANUARY 1976

By J. HARDING (Bracknell) and A. A. BINDING (Maidenhead)*

SUMMARY

A project is described in which surface wind and atmospheric pressure fields associated with 42 gales in the North Sea were prepared and wind and pressure tabulated for a network of gridpoints. The severe gale of 3 January 1976 is described in detail and reference is made to that of 31 January/1 February, 1953.

INTRODUCTION

This article will describe a project which was undertaken primarily to provide data for use with a numerical North Sea Wave Model (NORSWAM), and it is therefore of interest to give some background information to the NORSWAM study.

Operators engaged in fossil fuel extraction from the sea-bed of the United Kingdom continental shelf, and in particular of the North Sea, need wave information which is broadly speaking of two types:

(1) Accurate wave forecasts so that they can conduct their day-to-day operations as efficiently and safely as possible.
(2) Statistical information on waves for planning purposes and for use in the engineering design of offshore installations.

The situation with regard to both types of information was unsatisfactory: for operational forecasts, the methods which have been used for calculating the wave field from a given windfield do not use the considerable recent advances in this subject, while for extreme wave heights it is impracticable to obtain data of adequate geographic coverage, or of the duration which is desirable for reliable statistics.

The North Sea Numerical Wave Model which was formulated by the NORSWAM group of European scientists and is supported by a consortium

* The work described in this paper was carried out by the authors while in the employment of the Institute of Oceanographic Sciences.

of oil companies and the Departments of Industry and Energy, is being developed in response to these problems, to which it gives at least a partial solution.

It is clear that a numerical wave model which uses the knowledge gained in recent theoretical and empirical studies can make important contributions to operational forecasting if the other outstanding problem, that of providing accurate wind forecasts, can be overcome. It is perhaps less obvious that the model can also be used to provide better data on which to base estimates of long-term extremes. This is done by using it as a 'hindcast' model, as is now described:

The best estimates of the wind fields which occurred during a past storm event are fed into the model, and the corresponding wave fields are calculated. If the worst storms over a number of years are selected according to a suitable criterion, then the wave data which the model calculates can be used to make an estimate of the distribution of extreme waves over the same period, and this can be extrapolated to the longer periods for which extreme wave predictions are required.

The central advantage of the method is that it allows one to produce a wave data set whose extent in terms of both time and space is much greater than can be produced by instrumental measurement.

In the development of the model, it is logical that it should be first used in the hindcast mode. The most important reasons for this are:

(1) The possibility of providing accurately specified wind fields for the storms of interest.
(2) The availability of wave data at selected positions in a form suited to analysis and comparison with the output of the model.
(3) The considerable amount of work which is required on the specification of forecast windfields before progress can be made in the real-time use of the model.

In view of these it is clear that the model must be used in the hindcast mode during the proving and verification stages.

The project herein described was addressed to the specification of wind and pressure fields during past storms and used 'subjective' rather than 'objective' methods. That is, it relied on the hand analysis and reanalysis of synoptic weather charts, rather than the use of computer methods. It was considered that by reanalysing the relevant charts, using all the available data and paying due attention to temporal continuity an estimate of the wind fields could be made which was superior to currently available objective methods.

The resulting data have applications to other numerical models besides the wave model, in particular those which predict storm surges and the non-tidal current circulations which accompany them. In view of this, efforts have been made to ensure that the results are as widely applicable as possible.

One of the storms selected for analysis was the severe gale of 3 January 1976 and this will be described in detail in the belief that it is of wide interest to meteorologists.

The work was carried out by meteorologists employed by the Institute of Oceanographic Sciences, but who used accommodation and facilities provided by the Meteorological Office at Bracknell.

A full report on the analysis is available in the *Institute of Oceanographic Sciences Report* series, No. 55, by Harding and Binding (1978).

THE SPECIFICATION OF THE WINDFIELDS

Initially the decade 1965–74 was chosen as the period to be investigated, but latterly 1965 was dropped and some events from 1975 and 1976 were included.

An examination of the *Daily Weather Reports* of the Meteorological Office for the period 1965–74 produced a list of more than 200 occurrences of gales in the North Sea. It was recognized that the gales should be classified according to the prevailing weather patterns. This had significance from the point of view of fetch and therefore for the choice of area for wind analysis. Moreover, it facilitated the choice of a reasonable representation of the various weather patterns in the list of gales chosen for analysis.

Seven classes of depression were identified and the principles governing the classification are given below.

Class A—Depressions from the north-west and north

Sub-class a—Depressions which moved from Iceland to south Norway and the south Baltic.

Sub-class b—Depressions which moved from Iceland to the Shetland area and Denmark.

Sub-class c—Depressions which moved south along the Norwegian coast to south Norway and Denmark.

Sub-class d—Depressions which moved south-south-east or south-east from the vicinity of Ocean Station M (66°N, 2°E).

In general, associated gales in the North Sea were between west and north. There were occasional south to south-west gales, usually associated with depressions on the more westerly tracks.

Class B—Depressions which moved east to the south of Iceland

Sub-class a—Depressions and waves which moved east to the south of Iceland but north of the British mainland.

Sub-class b—Depressions which moved east from Iceland to Norway.

Sub-class c—Polar depressions which moved east or east-south-east from north of Iceland to Norway.

Gales were predominantly west to north-west. Wind directions sometimes veered as far round as north; whether or not this happened often depended on the history of the depression after reaching the Norwegian coast, for example, some might develop south-eastwards or even southwards rather than eastwards, with north-west to north gales in the North Sea. Sometimes a polar depression developed behind the main depression and moved south along the Norwegian coast. From time to time a development of this type produced a major gale in the North Sea.

Class C—North-eastward-moving depression in the North Atlantic

Gales in the North Sea were most frequently produced by this type. Broadly speaking they were north-eastward-moving depressions or waves over the North Atlantic, moving between Iceland and Scotland, but some which moved north-east through the Denmark Strait also led to gales in the North Sea.

A few of these depressions turned east while still to the west of Britain, while others did not turn east until they reached a point to the north. A few swung south-eastwards into the North Sea and across Denmark or south-eastwards across south Norway. Some became quasi-stationary near Iceland.

Gales in the North Sea associated with these depressions predominantly followed the direction sequence south-south-east to south-west to west to north-west. Depressions swinging south-eastwards into the North Sea might result in gales as far round as north.

Class D—Depressions or waves over or west of Britain which moved north or north-north-east

Usually there was an anticyclone over the continent, either with depressions west of Britain moving north, or deep depressions from the south-west turning north towards Iceland. Waves moving north over Britain between a continental anticyclone and an Atlantic depression would on occasions tighten the North Sea gradients sufficiently to produce gales.

Associated gales were mainly south to south-east and included some prolonged periods of gales or near gales, for example on 3–13 January 1974.

Class E—Ridge of high pressure to the north, and depressions to the south

Associated gales were mainly between east and north-east.

Class F—Depressions which crossed the North Sea, but excluding Class A and Class C depressions

Class F gales were a good second to Class C gales in frequency. They may be roughly sub-classified as follows:

Sub-class a—Depressions from Scotland and north-east England.

Those which moved north or north-north-east were mainly associated with gales between south and west.

Those which moved north-east were mainly associated with gales having a south-west to west and north-west sequence of directions.

Those which moved in directions between east-north-east and east-south-east were mainly associated with gales having a south to west to north sequence.

Only 2 out of 34 depressions in this sub-class moved south-east or south-south-east, one with west veering north-west gales and the other with north-west and north-east to east gales.

Sub-class b—Depressions from east and south-east England.

These depressions moved in directions between east and north-east. Gale directions were predominantly south-east backing east backing north-east, and south-west veering west veering north.

Sub-class c—Others.

One depression moved northwards from the continent, with gales between north-east and north.

Two moved south-west and then south from Denmark, with northerly gales.

Class G—Depression over Germany

There was one occasion of northerly gales over the central and southern North Sea associated with a depression over Germany. This depression had come from the south-east, deepening. It then moved away eastwards, filling.

SELECTION OF GALES FOR ANALYSIS

In all 215 North Sea gales were identified in the 10 year period 1965–74, and from these a sub-set had to be selected which adequately represented the main features of the most severe gales in that period.

It was realized that for reasons of cost and time the number of gales which could be analysed by a subjective method would be limited to about 50, and with such a comparatively small sample the task of selection would need to be approached with great care.

As a first step the original total was reduced by about 50 per cent by deleting the less noteworthy gales. This left 113 gales which again required reduction by more than half.

TABLE I—STORMS SELECTED FOR ANALYSIS

Year	Month	Class	Analysis Period (DDHH)	Analysis Area
1966	May	F	2200–2506	NN
	Nov/Dec	A	2818–0206	NN
	Dec	C	0700–0918	N
1967	Feb/Mar	C	2612–0215	NNA
	Dec	C	0206–0506	NNA
1968	Mar	B	1512–1912	NNA
1969	Mar	E	1206–1918	N
	Nov	A	2612–3012	NN
	Dec	D	1812–2300	N
1970	Jan/Feb	C	3112–0418	N
	Feb	F	1818–2200	N
	Oct	B	1612–2200	NNA
1971	Oct	C	2100–2400	NN
	Nov	B	1500–1818	NNA
	Nov	F	2000–2321	N
1972	Jan	F	2600–2906	NN
	Mar	D	0206–0506	N
	Nov	C	0806–1212	NNA
	Nov	F	1200–1412	NN
	Nov	C	1718–2106	N
1973	Feb	C	1012–1306	NNA
	Apr	F	0106–0406	NN
	Nov	B	1106–1418	NNA
	Nov	C	1706–2106	NN
	Dec	A	1118–1518	NNA
1974	Jan	D	0318–0621	NN
	Jan	D	1100–1403	NN
	Jan	F	1518–1812	NNA
	Jan	D	2700–3006	NN
	Feb	C	0912–1306	N
	Sept	F	0606–0921	NN
	Oct	G	2112–2412	N
	Oct	A	2612–3018	NNA
	Nov	C	1000–1312	N
	Nov	F	2318–2706	N
	Dec	C	1612–1918	NN
1975	Jan	B	0406–0718	NNA
	Jan	B	2106–2512	NNA
	Nov	F	2606–2906	NN
	Nov/Dec	F	3012–0412	NN
1976	Jan	F	0112–0500	NN
	Jan	B	1815–2306	NNA

DD = Day of month. HH = Hour of synoptic chart.
Analysis periods refer to the North Sea and, when analysed, to the northward extension to 70°N. Periods of Atlantic analysis usually differ from those of the North Sea.

N = North Sea.
NN = North Sea and northward extension to 70°N.
NNA = North Sea and northward extension to 70°N plus a selected area of the North Atlantic.

A. F. Jenkinson of the Meteorological Office has made an objective classification of weather types around the British Isles and has allocated an index of severity to gales in the area since 1881 (Jenkinson and Collison, 1977). Using this catalogue he selected a set of 56 periods for analysis. In carrying out the selection care was taken to preserve the distribution of gales when classified by type, monthly occurrence and annual frequency. At a later date the year 1965 was deleted from the investigational period and 1975 added, and again using Jenkinson's gale catalogue a selection of less vigorous gales was deleted. Furthermore, two gales from January 1976 with high severity indices were included. The final list of gales is shown in Table I together with the period and area of analysis.

The distributions of gales by year and by class in the final selection are shown below.

TABLE II(a)—DISTRIBUTION OF GALES BY YEAR IN THE FINAL SELECTION

1966	67	68	69	70	71	72	73	74	75	76 (Jan.)	Total
3	2	1	3	3	3	5	5	11	4	2	42

TABLE II(b)—DISTRIBUTION OF GALES BY CLASS IN THE FINAL SELECTION

A	B	C	D	E	F	G	Total
4	7	12	5	1	12	1	42

The distribution of gale classes by month is shown below.

TABLE III—DISTRIBUTION OF GALE CLASSES BY MONTH IN THE FINAL SELECTION

January	BBB	DDD	FFF		9
February	CCCC	F			5
March	B	D	E		3
April	F				1
May	F				1
June					
July					
August					
September	F				1
October	A	B	C	G	4
November	AA	BB	CCCC	FFFF	12
December	A	CCC	D	F	6

SPECIFICATION OF ANALYSIS AREAS

The windfields for the selected gales were specified at 3-hourly intervals, using the grid used in numerical forecasting by the Meteorological Office (Burridge and Gadd, 1977). Because of the importance of fetch the choice of analysis areas was varied from storm to storm. The areas are described below.

TABLE IV—DESIGNATION OF ANALYSIS AREAS

N—The North Sea.
NN—The North Sea and northward extension to 70°N.
NNA—The North Sea and northward extension to 70°N, plus a selected area of the North Atlantic.

It should be noted that area NNA varied from storm to storm. The 100 km grid was used in the North Sea and the 300 km grid elsewhere.

METHOD OF ANALYSIS WITH PARTICULAR REFERENCE TO THE DETERMINATION OF THE WINDFIELD

Synoptic weather charts as produced routinely within the Meteorological Office were used in the analysis work.

For the North Sea analysis the $1:3 \times 10^6$ British Isles series was used, and the relevant charts were borrowed from the London Weather Centre archive. The scale proved to be ideally suited to wind analysis and a 100 km grid.

For the analyses of areas outside the North Sea and for periods up to mid-1971 the $1:15 \times 10^6$ North Atlantic charts held in Meteorological Office archives were used. In mid-1971 these charts were replaced by charts with a scale of $1:20 \times 10^6$ and this scale was found to be inadequate for ease of isotach analysis. It was decided, therefore, to replot the observations on charts with scale $1:7{\cdot}5 \times 10^6$. Towards the end of the 10 year period this need for the preparation of new charts disappeared as similar charts were available from the Meteorological Office at London/Heathrow Airport.

Wind and pressure fields were specified every three hours throughout an analysis period. The surface windfield was derived primarily from a consideration of the surface pressure field, although reported winds provided essential additional information in all but the simplest pressure fields. The geostrophic winds were read from the charts by using the conventional transparent scale and it was then necessary to convert these geostrophic winds to surface winds. In order to simplify this task a table was prepared based on the work of Findlater *et alii* (1966). This is reproduced as Table V. Essentially it shows the amount by which a given geostrophic wind must be reduced and by how much it must be backed in direction under various conditions of flow, stability, and curvature in order to give the best estimate of the surface wind.

Isotachs were extensively used, and the tracking of isotach features proved to be a powerful method of analysis.

The values of wind speed and direction and pressure were read from the chart for each gridpoint and written on to specially prepared forms for subsequent transference to punched cards and ultimately to magnetic tape.

Accuracy of the wind and pressure fields

It has proved to be very difficult to make a quantitative assessment of the accuracy obtained in the specification of wind and pressure fields. What can be done is to consider the factors which affected the analysis and make subjective estimates of accuracy in different situations.

On this basis it is probably fair to say that many derived wind speeds are accurate to within ± 10 per cent or ± 3 knots whichever is the greater.

However, higher errors must be expected at some gridpoints at times, for example when winds were strong and isotach gradients steep. Wind directions were often correct to within 10°, but greater errors must be expected locally when there were vigorous changes in the pressure field. The smallest errors were probably attained in strong straight flow in unstable air.

The gales of early January 1976

The gales of early January 1976 were amongst the most severe to affect the British Isles and North Sea this century. Shaw *et alii* (1976) have written in considerable detail about the gales over the United Kingdom itself, where damage was widespread. A study of the detail of developments over the North Sea was possible only after the plotting of additional reports from various sources using knowledge of the reliability and systematic errors of wind and pressure measurements and using tracking techniques to determine the most probable intermediate situations between those that had been adequately

TABLE V—REDUCTION OF GEOSTROPHIC WINDS TO SURFACE WINDS

	Geostrophic Wind (kn)																									
Cyclonic flow	10		15		20		25		30		40		50		60		≥70									
Straight flow	10		15		20		25		30		35		40		50		60		70		80		90		100	
	Surface windspeed V_s and angle of backing β from geostrophic wind direction																									
Lapse rate (K/300 m)	V_s	β	V_s	β	V_s	β	V_s	β	V_s	β	V_s	β	V_s	β	V_s	β	V_s	β	V_s	β	V_s	β	V_s	β	V_s	β
≥3·1	10	0	15	0	18	0	23	0	25	0	30	0	32	0	36	0	40/43*	0	45/50	0	50/55	0	55/60	0	60/67	0
3·0–2·2	9	5	13	5	17	5	20	5	25	5	28	5	30	5	34	5	37/40	5	43/47	5	47/52	5	52/57	5	57/64	5
2·1–1·4	9	10	13	10	15	12	20	12	20	15	25	15	27	12	30	10	32/35	10	37/41	10	41/45	10	45/49	10	49/55	10
1·3–0·6	8	17	12	17	15	20	18	20	20	20	23	20	25	22	27	20	30/33	20	34/38	20	38/41	20	41/45	20	45/51	20
0·5–0·3	7	15	11	15	13	18	17	18	20	20	22	20	25	20	26	25	27/30	25	31/35	25	35/38	25	38/42	25	42/46	25

* The notation '40/43' means that the surface wind speed varies linearly with latitude from 40 kn at 50°N to 43 kn at 70°N.

documented. The eight synoptic charts for 3 January are illustrated in Figures 1–8 and the tracks of the parent and secondary depressions are at Figure 9. Developments in the windfield are readily followed by reference to the isotachs on the synoptic charts.

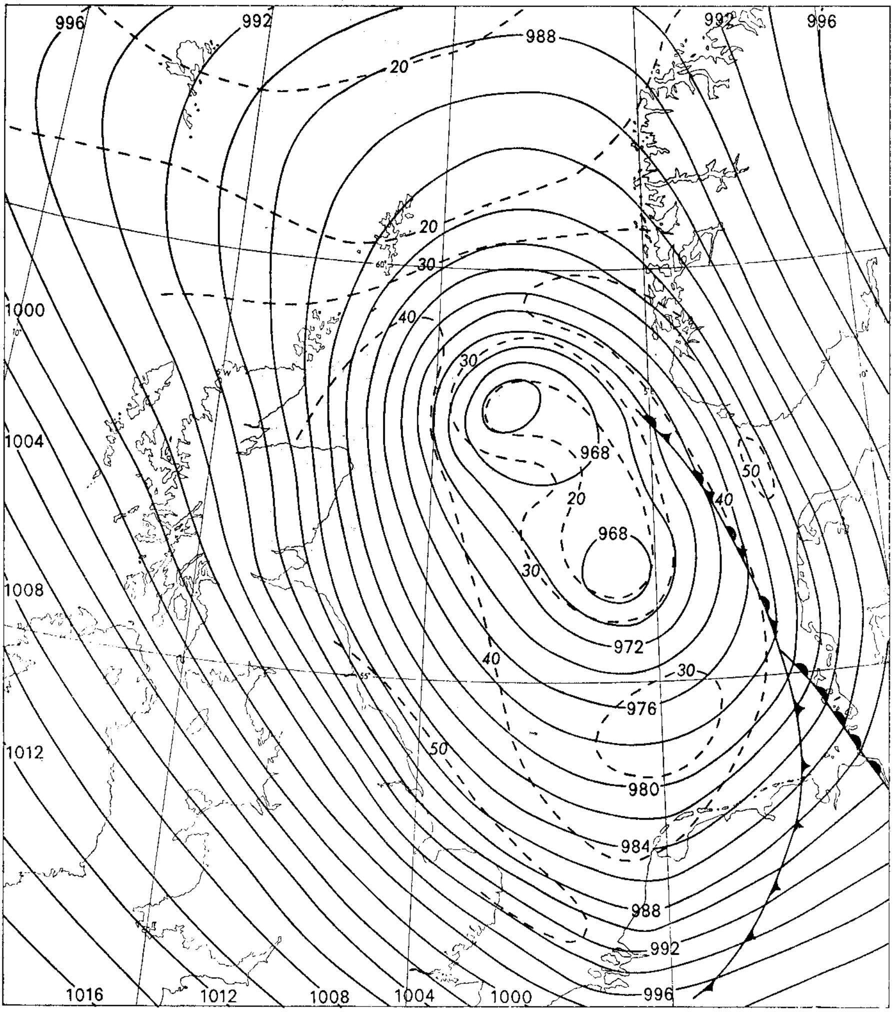


FIGURE 1—SYNOPTIC CHART FOR 00 GMT 3 JANUARY 1976
——— isobar (mb) – – – isotach (kn)

Having moved east-north-east from the Atlantic to a position over the western Highlands of Scotland by 1800 on 2 January, a small but vigorous and deepening frontal depression continued on the same track for another three hours, then turned east and later south-east. The centre deepened to its lowest pressure, estimated at 963 mb at 0300 on the 3rd, and slowly filled thereafter.

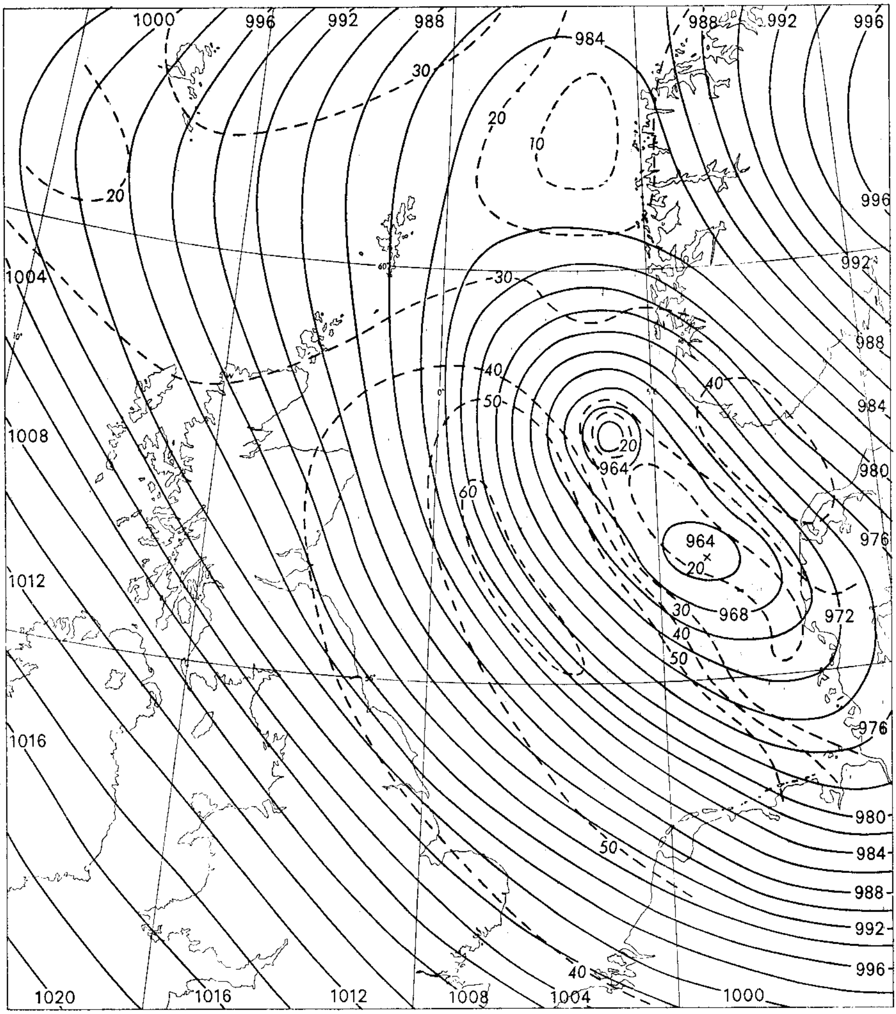


FIGURE 2—SYNOPTIC CHART FOR 03 GMT 3 JANUARY 1976
——— isobar (mb) - - - isotach (kn)

By 1800 on the 2nd the northerlies behind the deepening low had gained strength and fetch, causing severe troughing southwards from the centre, and as this process intensified a new depression centre formed in the trough soon after it crossed the east coast of Scotland, becoming evident by 2100. This centre moved almost due east, deepening to a minimum central pressure of 964 mb also at 0300 on the 3rd. Turning north-east after 0600, by 0900 it had coalesced over north-west Denmark with the original centre, and the combined centre then continued in a south-easterly direction with the same central pressure of 967 mb and later turned east-south-east, filling slowly.

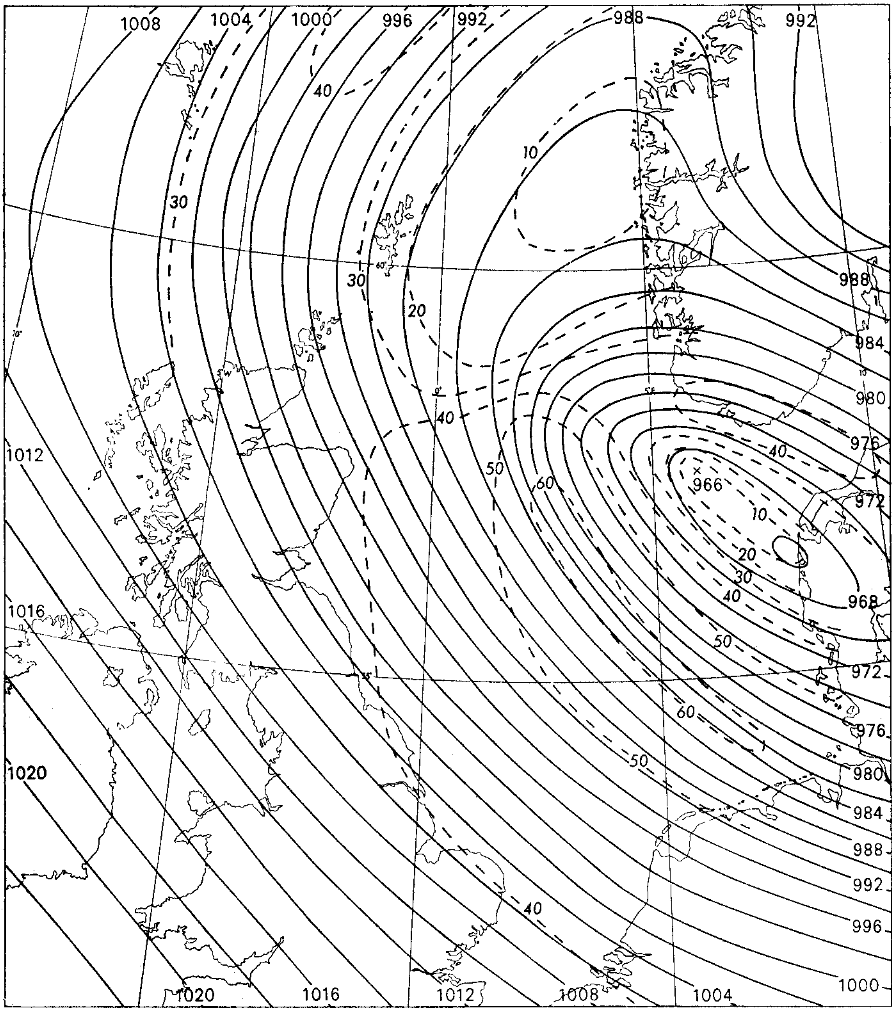
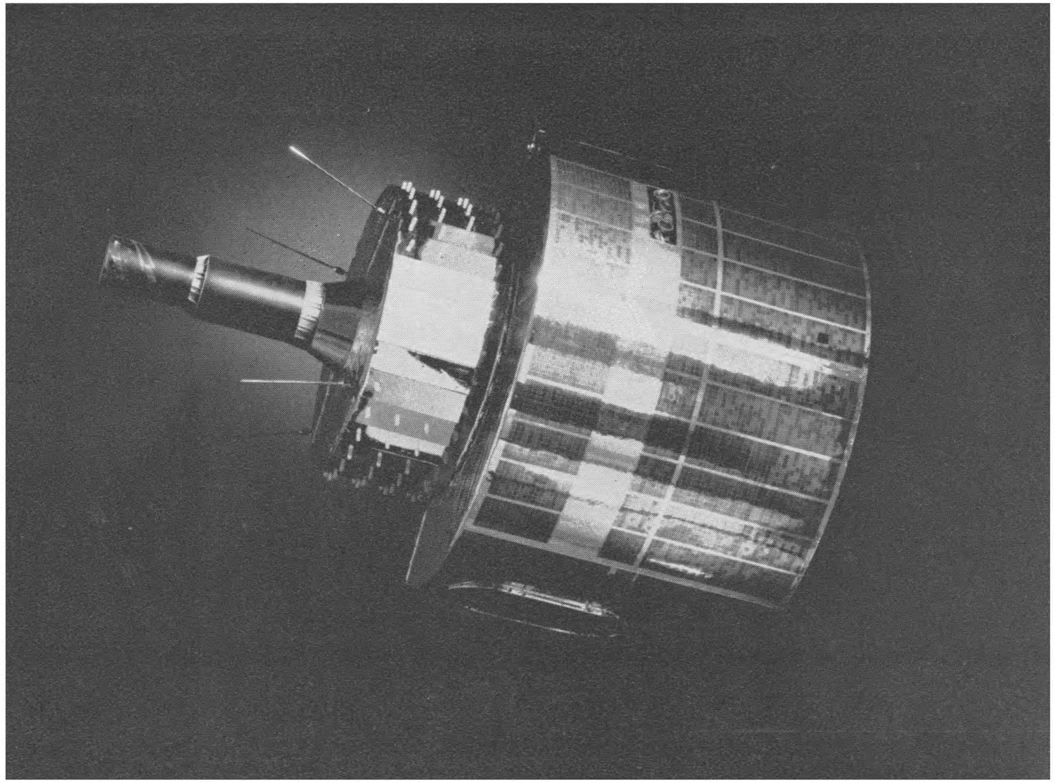


FIGURE 3—SYNOPTIC CHART FOR 06 GMT 3 JANUARY 1976
——— isobar (mb) – – – isotach (kn)

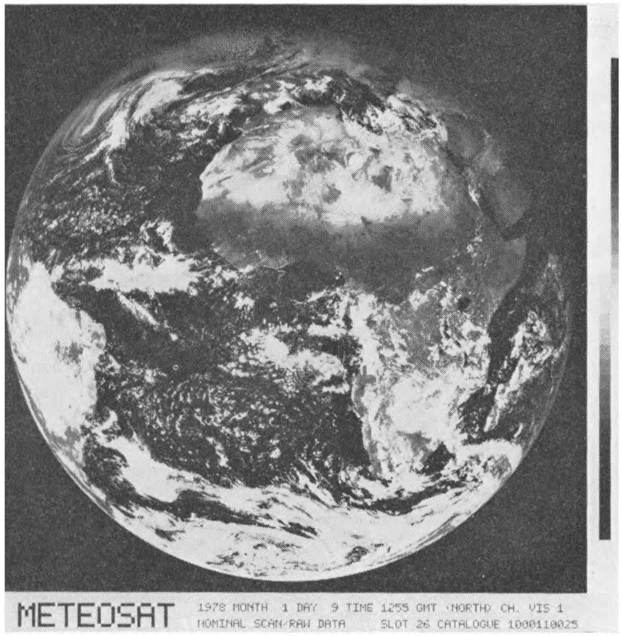
The north-westerly gales associated with the depressions had already reached the western North Sea by 0001 on the 3rd with a maximum mean wind exceeding 50 kn along the east coast of England. This increased to more than 60 kn as it moved very quickly east, broadly retaining its position relative to the centres of the depressions, then between 0300 and 0600 extended downward towards north-west Germany. Notable gusts at heights somewhat above 30 m reported from North Sea installations include 90 kn near $56\frac{1}{4}$°N $2\frac{1}{2}$°E at 0500 and 95 kn near 57°N 2°E at 0600. The maximum wind then transferred downwind as pressure rose strongly behind the centre, weakening the pressure gradient there, and between 1200 and 1500 passed into north-west Germany and the Danish border, where coastal gusts of 85 and 88 kn were recorded (Loader, 1976).

To face page 174

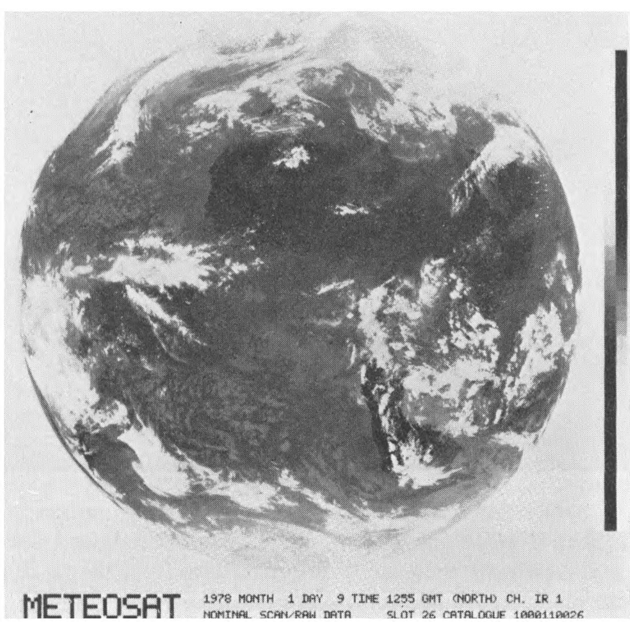


Photograph by Paul Genest for European Space Agency

PLATE I—FULL-SIZE MODEL OF METEOSAT, THE EUROPEAN GEOSTATIONARY SATELLITE
(See page 158.)


METEOSAT
1978 MONTH 1 DAY 9 TIME 1255 GMT (NORTH) CH. VIS 1
NOMINAL SCAN/RAW DATA SLOT 26 CATALOGUE 1000110025

(a)


METEOSAT
1978 MONTH 1 DAY 9 TIME 1255 GMT (NORTH) CH. IR 1
NOMINAL SCAN/RAW DATA SLOT 26 CATALOGUE 1000110026

(b)

(c)

Plate II—Meteosat images

(a) This 'visible channel' image was produced by the Meteosat radiometer between 1230 and 1255 GMT on 9 January 1978. The image is made up of 5000 scan-lines, each containing 5000 brightness values. The spatial resolution at the centre of the image is about $2{\cdot}5 \times 2{\cdot}5$ km.

(b) This is the corresponding image from the infra-red channel, with passband at around 11 μm. At this wavelength the atmosphere is almost transparent (hence the term 'window'). The image comprises 2500 lines, each of 2500 points, resolution 5 km. The hot land appears black; warm sea is dark grey; low cloud appears light grey; high and thick cloud is white. Note how, in conjunction with the visible image, one can interpret the cloud field in terms of its various layers.

(c) This is the image, also produced simultaneously, in a spectral band around $6{\cdot}3$ μm, where water vapour is strongly absorbing. One is seeing the upper troposphere; dry areas appear dark; moist areas appear light grey. Very high clouds show through as white. Meteosat is the first geostationary satellite to have a 'water-vapour' channel.
(See page 158.)

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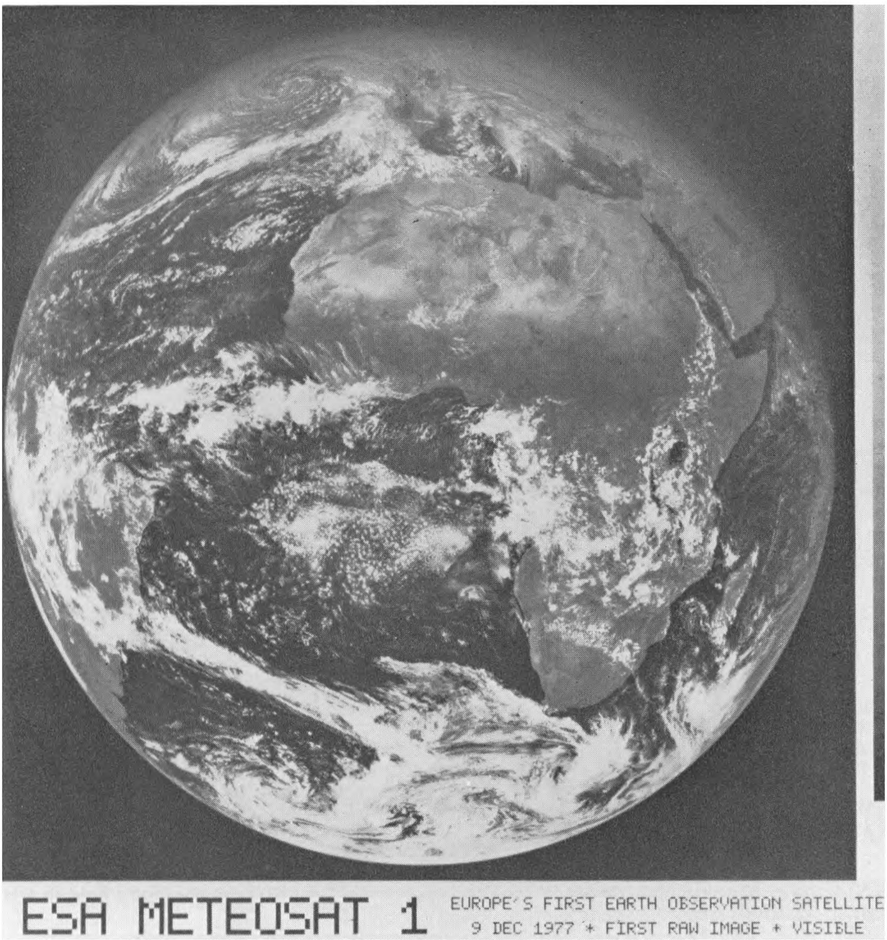

PLATE III—THE FIRST VISIBLE IMAGE RECEIVED FROM METEOSAT ON 9 DECEMBER 1977

(See page 158).

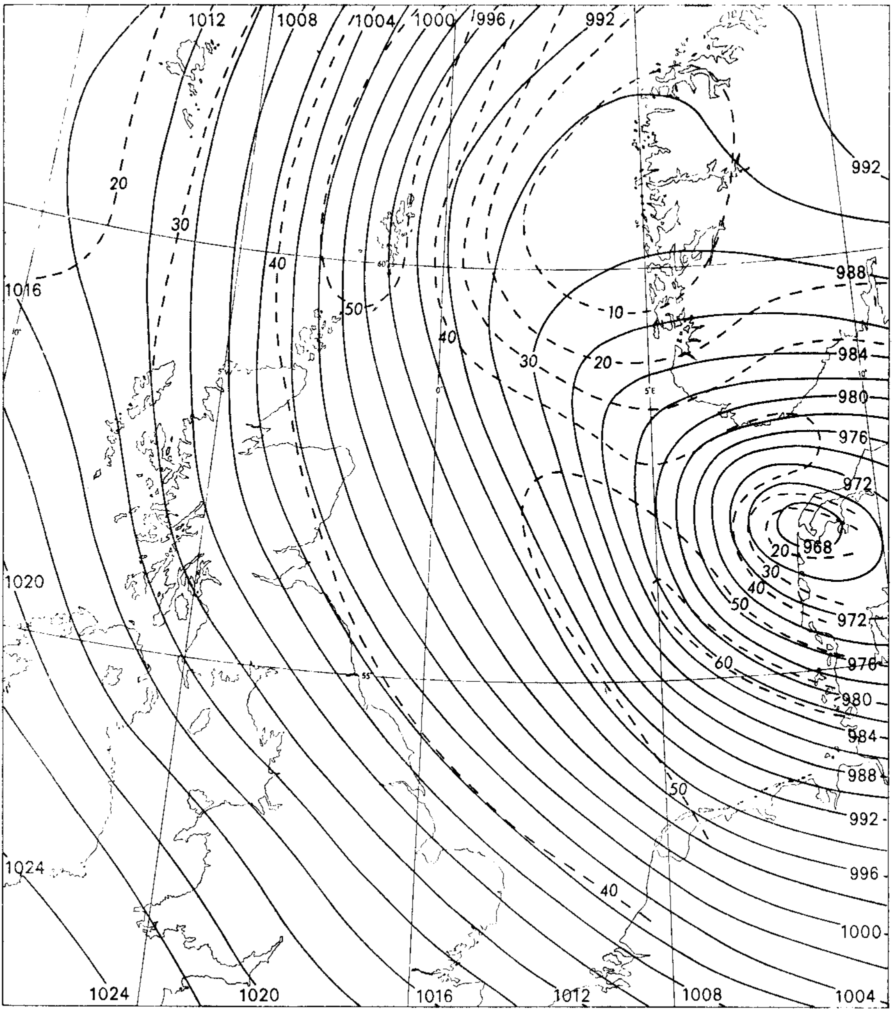

FIGURE 4—SYNOPTIC CHART FOR 09 GMT 3 JANUARY 1976
——— isobar (mb) – – – isotach (kn)

Meanwhile between 0000 and 0300 on the 3rd a well-marked trough developed off the Norwegian coast between about 60° and 65°N owing at least in part to orographic influence in the easterlies north of the depression, while a ridge of high pressure was moving east over the eastern North Atlantic. Pressure rose gradually in the trough which moved little during the next 12 hours, but as the ridge continued its eastward movement towards the British Isles pressure began to rise more strongly between 0300 and 0600 to the north-north-west of Scotland, increasing the pressure gradient between 0° and 5°W north of 60°N, and this process continued as the ridge continued to approach the almost stationary trough off Norway. The pressure gradient continued to increase and its maximum moved south and developed gradually eastwards, giving rise by 1200 to a

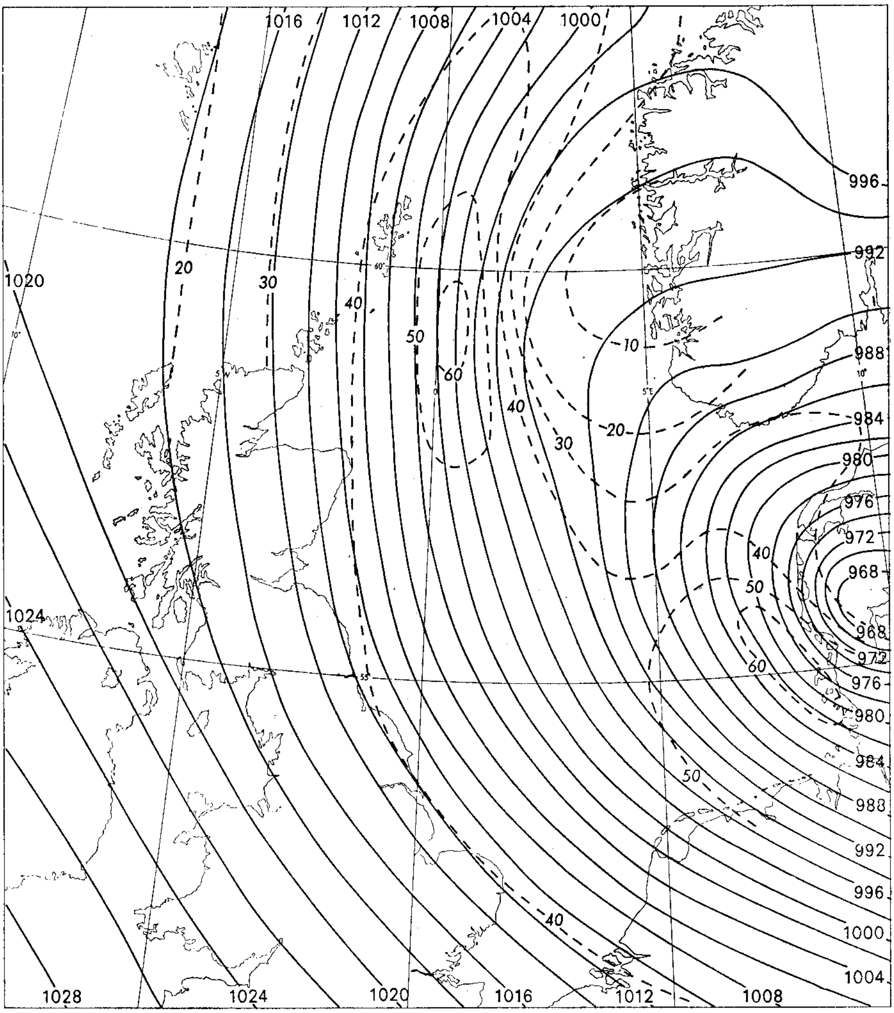

FIGURE 5—SYNOPTIC CHART FOR 12 GMT 3 JANUARY 1976
——— isobar (mb) – – – isotach (kn)

belt of northerly winds with a maximum of over 60 kn just east of the Greenwich meridian between 59° and 60°N. This maximum wind belt moved slightly east of downwind with little change in intensity until 1800. It then decreased while progressing south-south-east, the ridge approaching from the west having collapsed over the British Isles and the trough off south-west Norway having quickly moved south and filled. This rapid filling of the trough occurred as the easterlies over southern Norway died away, the causal depression having continued to fill and to move away east-south-eastwards. Notable gusts in this second burst of storm-force winds from the north were 90 kn at 0900 and 82 kn at 1200 in the extreme north of the Shetland Isles, 88 kn near 61¼°N 1¼°E

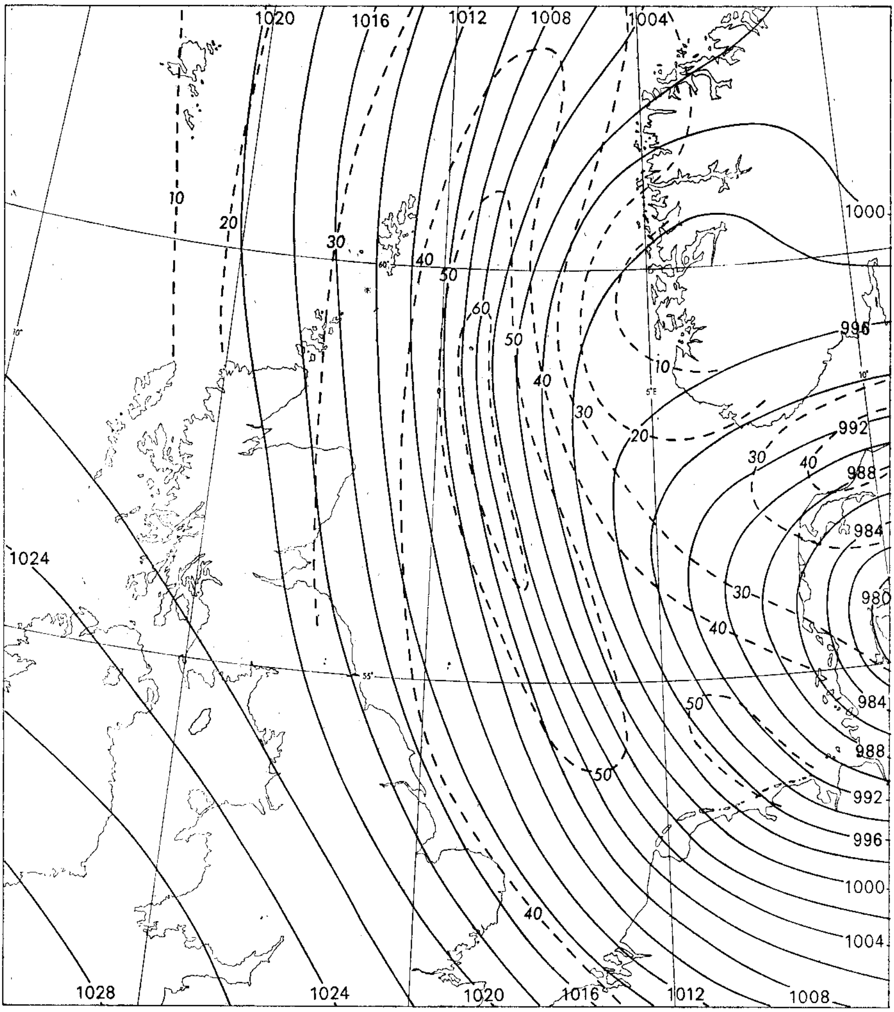

FIGURE 6—SYNOPTIC CHART FOR 15 GMT 3 JANUARY 1976
——— isobar (mb) - - - isotach (kn)

at 1200, 85 kn near 57°N 2°E at 1800 and 84 kn near 59½°N 1½°E at 1500, the last three quoted being from North Sea installations at heights above 30 m. It is also interesting that at an installation near 61°N 2°E the wind speed increased from 16 kn to 60 kn in the 10 minutes preceding 0900, not unexpectedly at a time and place where a very steep isotach gradient existed.

It has been a natural reaction in any study of this gale to recall that of 31 January/1 February 1953 over the United Kingdom and North Sea. Douglas (1953) reported on the latter. Shaw *et alii* (1976) refer to it when comparing the associated tidal surges in the North Sea on the two occasions.

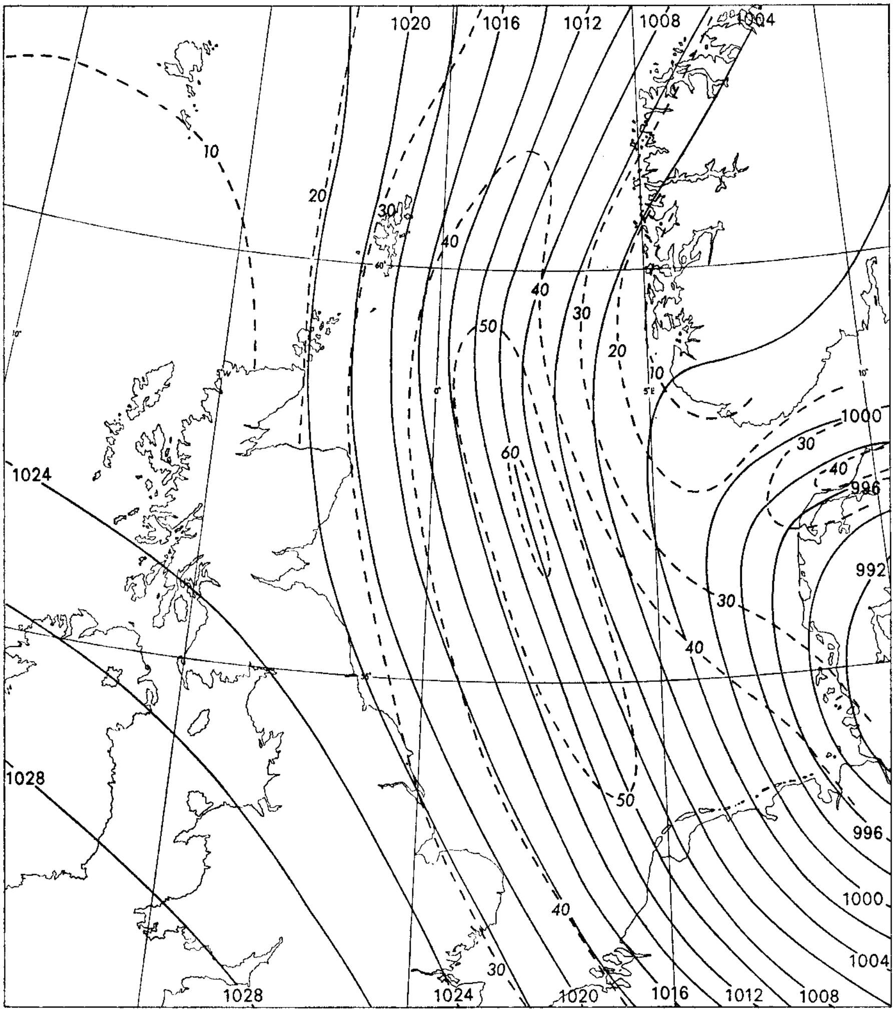

FIGURE 7—SYNOPTIC CHART FOR 18 GMT 3 JANUARY 1976
——— isobar (mb) - - - isotach (kn)

Loader (1976) draws comparisons between them both synoptically and in respect of tidal surges in the North Sea. Inspection of the 1953 charts reveals an almost complete absence of observations over the North Sea with the exception of light-vessel reports near coasts. It would be impossible to carry out a wind analysis with the same confidence as for that of the period from 1966. However, conclusions can be drawn from the charts from which comparisons can be made with the 1976 gales.

The 1953 depression originated on the warm front of a depression which was moving towards the Azores from the north-west. It moved north-eastwards

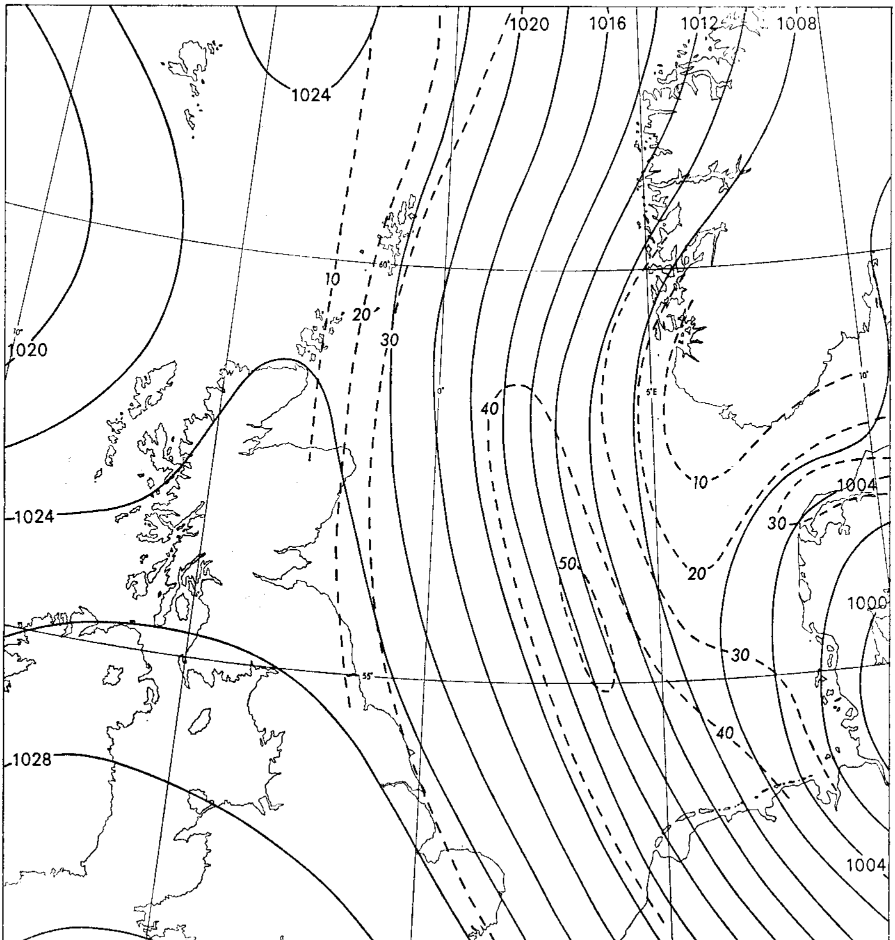

FIGURE 8—SYNOPTIC CHART FOR 21 GMT 3 JANUARY 1976
——— isobar (mb) - - - isotach (kn)

and then eastwards to a position between Scotland and Thorshavn and then south-eastwards between Scotland and the Shetlands and across the North Sea and Helgoland Bight. An outstanding feature of this depression was the intense broad northerly flow over Scotland behind the depression. Douglas (1953) estimated that the geostrophic wind reached 150 kn in a belt over 100 miles wide and that there was a long belt with a geostrophic wind averaging about 120 kn over the whole of the western and central parts of the North Sea as the depression moved south-east towards the Helgoland Bight.

The 1976 depression had a somewhat similar origin, breaking away from an area of low pressure to the west of the Azores and moving north-eastwards to Scotland. It subsequently moved east and south-east across the North Sea and Denmark—see Figure 9 below. Shaw *et alii* (1976) studied in detail the low-level winds over the United Kingdom. They found evidence of geostrophic winds of 150 to 160 kn over Lancashire and the Sheffield area.

The tracks of the two depressions were significantly different, with corresponding major differences in the distribution, fetch and direction of the gales in the North Sea. There were also significant differences in the development of the two depressions. As described earlier in this section a secondary depression

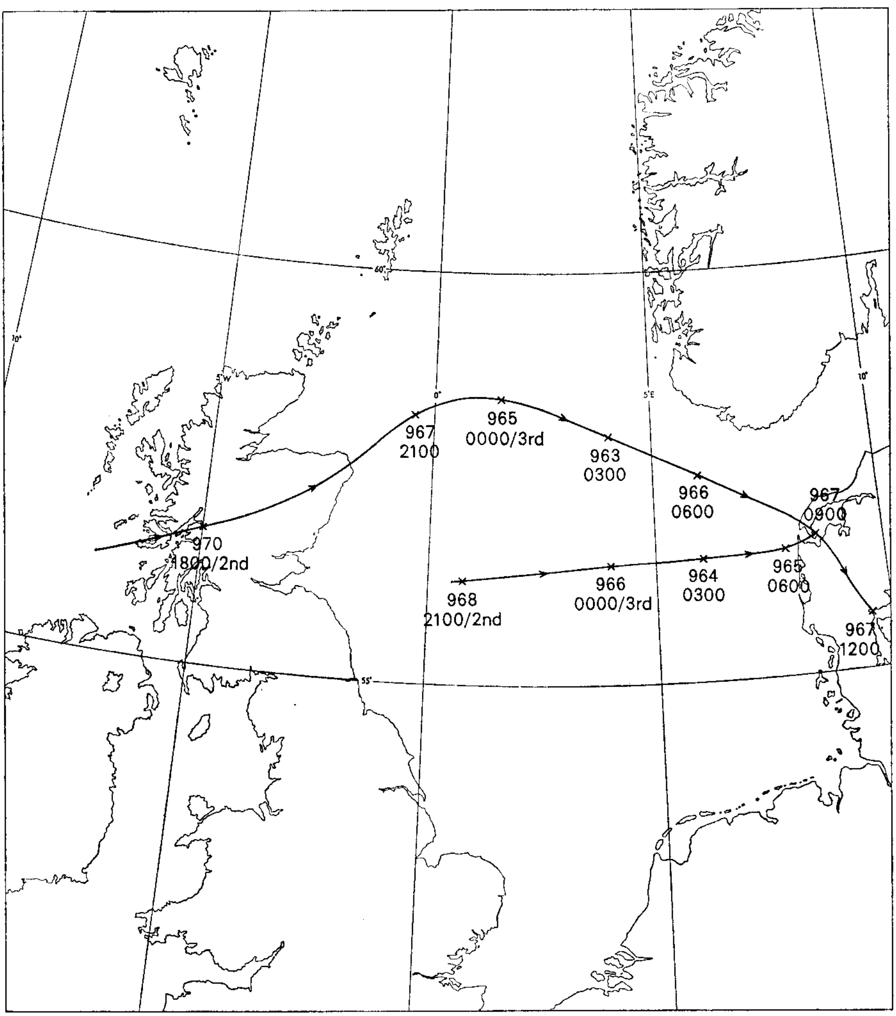

FIGURE 9—TRACKS OF DEPRESSIONS WITH CENTRAL PRESSURES AND TIMES

formed in the severe troughing behind the 1976 depression and the two depressions coalesced over Denmark as illustrated in Figure 9. There was well-defined troughing behind the cold front of the 1953 depression but there is no evidence to suggest that a secondary depression existed at any time in this trough. Any secondary developments were weak and associated with the frontal system to the east of the depression. This is also the interpretation of Mr J. Sanders of the Koninklijk Nederlands Meteorologisch Instituut, who kindly supplied his synoptic reconstruction of the 1953 gales. The isotach maximum moved south-eastwards from North Scotland to the Netherlands more or less parallel to the track of the depression. Herein lie the major differences between the 1953 and 1976 gales. The synoptic charts at Figures 1–8 clearly illustrate the existence of two isotach maxima both of which exceeded 60 kn at peak development. The first was closely associated with the depression itself and its secondary whilst the second and more unusual maximum was associated with the interplay between the advancing Atlantic high-pressure ridge and the trough off the Norwegian coast. It is this secondary maximum that has made the 1976 gales of especial meteorological interest.

Availability of report and data

A detailed account of the work appears in the *Institute of Oceanographic Sciences Report*, No. 55, 'The specification of wind and pressure fields over the North Sea and some areas of the North Atlantic during 42 gales from the period 1966 to 1976' (1978) by J. Harding and A. A. Binding. Copies of the wind and pressure data for the 42 gales are available from the Marine Information and Advisory Service, Institute of Oceanographic Sciences, Wormley, Godalming, Surrey GU8 5UB.

Acknowledgements

The authors gratefully acknowledge the co-operation of the Director-General of the Meteorological Office during the investigation described in this article. Our thanks are also due to IMCOS Marine Ltd for the supply of data from North Sea structures. The work was supported financially by the Departments of Industry and Energy and the United Kingdom Offshore Operators Association and this article is published with their approval.

References

BURRIDGE, D. M. AND GADD, A. J.	1977	The Meteorological Office operational 10-level (numerical weather prediction model December 1975). *Sci Pap, Met Off,* No. 3 4
DOUGLAS, C. K. M.	1953	The gale of January 31, 1953. *Met Mag,* **82,** pp. 97–100.
FINDLATER, J., HARROWER, T. N. S., HOWKINS, G. A. AND WRIGHT, H. L.	1966	Surface and 900 mb wind relations. *Sci Pap, Met Off,* No. 23.
JENKINSON, A. F. AND COLLISON, P.	1977	An initial climatology of gales over the North Sea. Unpublished, copy available in Meteorological Office Library, Bracknell.
LOADER, C.	1976	The storm of 2–3 January 1976. *J Met, Trowbridge,* **1**, pp. 273–283.
SHAW, M. S., HOPKINS, J. S. AND CATON, P. G. F.	1976	The gales of 2 January 1976. *Weather,* **31,** pp. 172–183.

551.5 93.653

NOCTILUCENT CLOUDS OVER WESTERN EUROPE AND THE ATLANTIC DURING 1977

By D. H. McINTOSH and MARY HALLISSEY

(Department of Meteorology, University of Edinburgh)

Table I summarizes the observations of noctilucent clouds (NLC) made over western Europe and the Atlantic during 1977 and reported to the Department of Meteorology, Edinburgh University. A grant from the Meteorological Office finances the collection, collation and publication of these data.

Observers' reports, positive or otherwise, were requested for the months May to August, and as in previous years the period mid-May to mid-August encompasses the main observing season—only a possible sighting from Norway in early September is entered in the list outside these dates. The times in the second column of the Table are not necessarily the total duration of the display. Voluntary observers are obviously unable at times to record a display to the point of disappearance, and tropospheric cloud interference may be such as to allow only short periods of observation; nor can professional observers, whose routine observations are made once per hour, always be sure of the exact time of appearance or disappearance of NLC, though in many instances these have been given.

In the third column of Table I, brief notes on the displays develop slightly the facts given in figures in the remaining columns—details of the relevant station co-ordinates to the nearest half degree, the maximum elevation and limiting azimuths of the observed NLC, where known—and refer to photographs and other points of interest.

TABLE I—DISPLAYS OF NOCTILUCENT CLOUDS OVER WESTERN EUROPE AND THE ATLANTIC DURING 1977

Date—night of	Times UT	Notes	Station position*	Time UT	Max. elev.	Limiting azimuths *degrees*
14/15 May	2300, 0200 0300	Faint bands of NLC visible.	57·5°N 03·5°W 55·5°N 01·5°W 55°N 04·5°W	0200 2300 0300	6	360, 045
15/16	2300 0200	No details.	55·5°N 01·5°W			
17/18	2305 0100	NLC partly obscured by tropospheric clouds at more northerly station, and by 0200 cloudy conditions prevailed.	57·5°N 03·5°W 55·5°N 04·5°W	0100 2305	14	020
20/21	2145 2300 2320–0110	Vertically banded area of eastern section of NLC spreading farther south than main cloud field of horizontal bands.	59°N 03°W 56·5°N 07°W 55°N 04·5°W	2330 2300 2145	25 20	340–360 270–360 330–020
21/22	0200	NLC suspected just visible above encroaching tropospheric cloud. NLC not visible in previous or later routine observations.	56·5°N 07°W	0200		025
28/29	0200	NLC veil of medium brightness.	54°N 04·5°W	0200	10	360–060
29/30	2400	Greenish-white glow partly obscured by tropospheric clouds recognized as probable NLC.	56·5°N 03°W	2400		360

* To nearest 0·5 degree.

TABLE I—*continued*

Date—night of	Times UT	Notes	Station position	Time UT	Mox. elev.	Limiting azimuths *degrees*
1/2 June	2314–2349	Banded NLC of moderate brightness seen low in north-west during the early observation. The observer—assuming NLC height of 82·4 km—provided details of cloud speeds and airflow direction (average measured speed 31 m s^{-1} towards 168°); display reported as 'extensive' at later time of maximum spread south.	56°N 04·5°W	2314	5	324–340
	0100			2349	6	318–338
	0345		55°N 04·5°W	0345	20	345–100
			54°N 04·5°W	0100	10	360–020
3/4	0100	Small patch of 'pearly-white' NLC.	56·5°N 07°W	0100	8	345
5/6	2200–2400	NLC visible through breaks in tropospheric clouds—no details of forms.	55·5°N 01·5°W			
8/9	2320–0310	Early sightings SW England and N. Ireland—formation of veil, bands (SW–NE) orientation with cross billows and 'thick' patches of brighter NLC—these latter possibly identified as whirls from two stations. From 0225 to 0245 billow formation seen from N. Ireland in ESE direction. Display generally of medium brightness.	54·5°N 06°W	0110	15	350–030
				0230	90+	090–120
			55°N 01·5°W	0100	15	330–020
			53·5°N 07·5°W	0220	17	330–070
				0240	35	310–080
				0300	12	
			52°N 02·5°W	2350	35	045
12/13	2400	Patch of bright NLC—whirl formation noted.	57°N 02°W	2400	40	345
13/14	2200–0240	Widely observed display of NLC in spite of hampering effect of mist in many areas—visible for duration to observer near Glasgow, who supplied photographs (1 second exposures 0010 to 0100) and detailed notes of geographical position, rate of movement and estimated height (average measured speed 49 m s^{-1} towards 220°). Gradual movement eastwards of the well-defined cloud area. Collectively, all forms seen. Photographs taken Malin Head at 0020 and 0042 show unusual amount of 'turbulence'. Brightness of display '4' for westerly placed stations.	56·5°N 03°W	0100	30	350–030
			56°N 04·5°W	0100	20	345–020
			55·5°N 05·5°W	2245	15	360
				2300	30	340–010
				2400	30	340–030
				0100	20	340–045
			55·5°N 07·5°W	2355	9	350–030
				0037	10	357–035
			55°N 04·5°W	2255	17	345
			55°N 03°W	2300	8	020–026
			54°N 04·5°W	2300	10	010
				2400	10	360–020
			53·5°N 07·5°W	0215	10	020
14/15	2346–2400	NLC visible at stations in same longitude in north of Ireland and western Scotland. Veil of earlier sighting soon obscured. Bright bands and billows of later sighting lost in brightness of sunrise.	57·5°N 07·5°W	0100	12	330–360
				0200	10	330–010
			55·5°N 07·5°W	2346	5	291–297
15/16	2200–0200+	NLC visible in both western and eastern Scotland. Bands, billows and whirls developed from early veil—the rippled and striated veil described as 'chaotic' on eastern edge; sketch shows the 'rippled' areas at each end of azimuthally extensive display.	57·5°N 07·5°W	2200	10	330–010
				2300	10	330–360
				2400	15	290–360
				0100	10	330–010
			57°N 02°W	0100	30	300–050
			56·5°N 07°W	2310	21	290–040
				0100	18	300–050
				0200	20	320–080
			56·5°N 03°W	2400	10	340–030
				0100	30	330–080
19/20	2400	2–3 patches of NLC in NW and NNE. Sky reported clear of NLC in previous and later routine observations.	56·5°N 07°W	2400	10	300–320
	0100				8	010
				0100	8	330–030
21/22	2330–0100	Faint band of NLC visible around midnight—most southerly station suspected the glow to be aurora, but this being clearly unlikely, the observation was recorded as a questionable NLC sighting.	55°N 04·5°W			
			54°N 04·5°W	2400	15	350–020
			53·5°N 01·5°W	2400	45	315–360
22/23	2115, 2305	Faint veil of NLC.	57·5°N 07·5°W	0100	10	330–360
	0100, 0200			0200		
			55°N 04·5°W			

TABLE I—*continued*

Date—night of	Times UT	Notes	Station position	Time UT	Max. elev.	Limiting azimuths *degrees*
23/24	2120–0230	Early development of NLC as seen SW Scotland first considered suspect, but by 2230 display outstanding, spreading W–NE. Seen at this time from 52°N, where effect of haze made NLC patches featureless, though slightly farther north the bands and billows were seen as 'tangled and dense'; viewing here also soon weakened by haze. Bright whirls seen at 2300 from N. Yorks., Northumbria and S. Scotland.	57·5°N 03·5°W	2400	20	340–045
			55·5°N 01·5°W	2300	15	360
				2400	15	360–045
				0100	17	350–040
				0200	28	
			55·5°N 03°W	2200 2300		315–360
				0200		045
			55°N 04·5°W	2230		270–045
			55°N 01·5°W	2245	15	320–020
			54·5°N 01·5°W	2300	15	318–020
				2400	9	330–020
				0100	9	340–040
				0200	24	355–080
				0210	45	330
			53°N 0·5°W	2300	11	330–025
				2400	7	340–020
				0200	20	350–070
				0225	50	070
			52°N 0·5°W	2250	7	320–360
26/27	2135–0225	From Northumbria no NLC seen 2300 but at 2315 thin bands to 15° were seen in NE; before midnight NLC suspected visible from Bedford. Bright billow formation reported from N; later southerly station noted billows and whirls in E part of display.	56·5°N 03°W	0100	20	030–050
			55·5°N 01·5°W	2315	15	020–050
				0100	15	030–050
			52°N 0·5°W	2400	3	—
				0150	8	360
				0207	5	010
27/28	0215–0300+	Almost 8/8 tropospheric cloud cover broke sufficiently to reveal very bright NLC band. No further observation possible.	54·5°N 06°W	0215	15	330–020
				0300		350–040
2/3 July	2055–2225 0045–0115	Earlier display bright formation of bands and 'knots' seen from Denmark—photographed 2142 and 2144. NLC stretching into SE when 'lost' in moonlight and tropospheric cloud. From NE Scotland small rippled patch visible for half hour just E of N.	57°N 02°W	0100	12	360–010
			55°N 14·5°E	2055	20	360
				2140	15	045–090
				2225		135
3/4	2400	Faint traces of NLC partly obscured.	55·5°N 01·5°W	2400	6	360
4/5	2150	Very faint NLC in NW, billowed structure identified through binoculars. (Entire E sky and parts of N sky covered by tropospheric clouds.)	55°N 14·5°E	2150	22	315
5/6	2300–0300+	NLC first sighted from west central Scotland as very faint band at high elevation; last sighting from same station when bright whirls still visible overhead. All stations reported, and some sketched, bright and extensive display of classic forms at high elevation.	57°N 02°W	0045	29	305–350
				0125	30	325–040
				0145	50	340–040
				0205	50	340–040
			56·5°N 03°W	0200	90	330–020
			56°N 04·5°W	0110	19	345
				0200	20	340
				0220	21	340
			55·5°N 04·5°W	2300	40	360–030
				2400	30	350–010
				0200	90	320–020
				0300	90	—
			55·5°N 01·5°W	0100 0200	25	330–030
			55°N 04·5°W			
6/7	2400, 0250	Earlier sighting of faint band of NLC, W–E orientation. Later short-lived sighting of faint rippled patch.	56°N 04·5°W	0250	33	020
			55·5°N 05·5°W	2400	14	350
9/10	2330–0240	First suspected visible behind tropospheric cloud by observer in SW Scotland, then seen as amorphous veil above mist from northern Ireland. Greatest spread southwards approx. 0220. Billows and whirls noted from Benbecula.	57·5°N 07·5°W	0100	13	290–350
				0200	8	300–360
			56·5°N 07°W	2400	11	320–030
				0100	11	320–040
				0200	18	320–090
			55·5°N 07·5°W	2400	8	360–020
			55°N 04·5°W	2330		
				0200		
			54·5°N 06°W	0200	11	330–080
				0220	17	330–020
					10	040–080
			53·5°N 03°W	0200	10	010–030
				0218	15	010–030
				0225	18	010–030
				0235	16	010–030

TABLE I—*continued*

Date—night of	Times UT	Notes	Station position	Time UT	Max. elev.	Limiting azimuths *degrees*
11/12	0100–0215	Bright bands, 'strongly defined', as seen from Tiree.	56·5°N 07°W	0100	20	330–060
				0200	30	330–020
			55·5°N 07·5°W	0100 0200	5	355–010
			55°N 04·5°W	0145	7	345–045
14/15	0145	Faint NLC of large horizontal extent.	55°N 04·5°W	0145	8	020
15/16	2145–2305 0130 0210, 0300	Faint NLC seen earliest from Denmark—extensive new formations in ENE with bright bands and billows. Photographs 2205–2240. Extensive spread of NLC noted from Roden (Netherlands); multiple bands, photograph 0130. Latest report from N. Ireland: banded formation.	55·5°N 10°E	2145	—	315–020
				2230	—	060
				2305	—	—
			54·5°N 06°W	0210	10	350–040
				0300		
			53°N 06·5°E	0130		
16/17	2400, 0100	W–E banded formation, with veil stretching southwards to observer's zenith on W side of display.	57·5°N 03·5°W	0010	90	330–360
					30	340–050
17/18	0200	NLC—no details.	54·5°N 01·5°W	0200	10	360–020
19/20	2215–0130	Greatest elevation in early part of observing period—faint, striated patches. Little movement.	55·5°N 01·5°W	2215	13	360–040
				2355	6	010–020
				0100	7	010–030
20/21	2305–0038	Banded formation NLC rising from NNE: slowly increasing brightness: westward movement. When obs. ceased (not end of display) bright bands visible spreading southwards at right angles to horizon. Display photographed 2345–0050.	56°N 10°E	2305	10	020
21/22	2258, 2305	In very good observing conditions no NLC until very faintly apparent at 2258, visible through binoculars. Drifting tropospheric clouds hampered observations but NLC had become visible to naked eye by 2305.	56°N 10°E	2258	5	020
22/23	2300–0150	At 2300 NLC visible from Norway and suspected from NE Scotland. At 0130–0150 veil seen from Norway—'illuminating eastern half of sky sufficiently to light up details of countryside'—and from NE England—'now brighter and striated'.	59°N 09°E	2300 2330	50	360–045
				0130	90+	090
			57°N 02°W	2300	—	315, 360
			55·5°N 01·5°W	0100	4	—
				0150	8	010–030
25/26	0220–0245	NLC patches aligned from NNW–ENE.	55°N 04·5°W	0230	12	010
26/27	2200–2230, 0020–0125	Faint NLC visible, through binoculars above tropospheric cloud. New patches appearing later, extending westwards; fast development in E and quickly increasing brightness. Observations ended with dawn. Photographs 0100–0113.	56°N 10°E	2200	12	—
				0020	8	
				0125	18	345–090
28/29	0050–0300	Very low elevation NLC bands appearing intensely bright as seen Tiree, less bright from Malin Head and behind haze from SW Scotland.	56·5°N 07°W	0100	1	—
				0200	4	360–030
				0300	5	025–040
			55·5°N 07·5°W	0100	3	345–360
			55°N 04·5°W	0250		
30/31	0240	Probable NLC.	55°N 04·5°W	0240		
31 July/1 Aug.	0348, 0403	Aircraft captain's observation of striated veil spreading NE towards SW. Later observation noted band and billow formation and higher elevation.	54°N 28°W	0348	5	350–050
			54°N 24°W	0403	11	360–035
1/2 Aug.	2030, 2040 0145–0330	Early sighting Denmark at high elevation—moderately bright NLC bands W–E aligned. Later observations from NE and central England: bands and whirl formation to fairly high elevation taking account of lateness in observation 'season'.	55·5°N 01·5°W	0145	7	360–020
				0220	8	
				0230	10	340–070
				0235	14	
			55°N 14·5°E	2030	25	345–360
			55°N 01·5°W	0300	20	010–070
			52°N 0·5°W	0255	10	010–040
				0305	10	020
				0315	9	020
				0330	10	010

TABLE I—*continued*

Date—night of	Times UT	Notes	Station position	Time UT	Max. elev.	Limiting azimuths degrees
2/3	0200, 0300	Bright bands seen Tiree; fainter by 0300 with slight recession of W edge.	56·5°N 07°W	0200 0300	4 4	340–030 350–030
6/7	2200	Isolated band of NLC, medium brightness at high elevation.	56·5°N 07°W	2200	40	340–360
9/10	0310	2 bands of NLC to high elevation, aligned NNE–SSW.	56·5°N 03°W	0310	80	020
10/11	0220	Trace of very faint NLC—simultaneous appearance of aurora.	59·5°N 01·5°W	0220	15	020
11/12	2300, 0015	Small area of NLC—'the cloud was bright enough to readily attract attention, having a pale lilac-coloration'. Small area of billows in veil. Simultaneous auroral appearance as NLC fading.	59·5°N 01·5°W	2300 0015	10	020
14/15	0215–0240	NLC visible at high altitude.	59°N 09°E	0230		060–100
15/16	2058–2135	Bright striated NLC with dense patches, WNW–ESE orientation almost in observer's zenith—obscured after 2135 by prevailing haze.	51·5°N 02°W	2050	87	—
7/8 Sept.	2015–2045	Diffuse but weak spread of NLC over much of sky.	59°N 09°E			

Positive reports of NLC were received from some 22 stations of the Meteorological Office network in Great Britain and from two stations of the Irish Meteorological Service network. Reports from many voluntary observers included those from the Fair Isle lighthousekeeper, the captain of an aircraft over the eastern Atlantic and experienced contributors to these lists observing from scattered points throughout Denmark, The Netherlands, Norway and the United Kingdom. Photographs and sketches were a helpful accompaniment whenever provided.

Routine observations for hours of darkness were received from 16 Meteorological Office stations and form an important part of the data collection, particularly where conditions are such that an observer is able to state with confidence 'No NLC'. These 'negative' reports are regarded as significant, particularly for nights during a possibly unbroken series of appearances of NLC. They are also a helpful point of reference when NLC is suspected by some observer in the vicinity. The high standard of all the reports received is greatly appreciated.

Table I records NLC sightings on 50 nights. Many of them were single-station 'definite' reports, but there is no hesitation in including such uncorroborated reports from experienced observers when sightings from neighbouring stations are prevented by lower cloud. With the high amount of tropospheric cloudiness recorded throughout the whole observing season it was fortunate that the infrequent clear periods were used to such good purpose. The displays of 13/14 and 23/24 June were the most widely observed. There were no outstanding displays, though on many occasions details of the cloud formation were clearly visible and described from different angles of view. Occurrences of the clouds were fairly evenly spread over the three two-week periods from mid-June to end-July, rather than showing concentration into a more usual 'peak' in the second half of June and/or the first half of July. It is notable, too, that no NLC appearances were reported from Denmark until early July, while, generally, the number of appearances of the clouds in August is greater than usual. This may in part be accounted for by somewhat better observing conditions, i.e. less tropospheric cloud, as well as greater awareness that the clouds may still (in principle) be observed then; observers at Lyneham would, even so, no doubt be surprised to record a sighting of NLC as late as 15/16 August.

Time-lapse photography of NLC was carried out throughout most of the observing 'season' from Edinburgh. There were, however, no 'clear' displays, camera trouble or tropospheric cloud interfering on all occasions. Displays for which photographs have been received from observers are 13/14 June (Milngavie and Malin Head), 2/3 July (Rønne, Denmark), 15/16 July (Håstrup, Denmark and Roden, The Netherlands), and 20/21 and 26/27 July (Alrø, Denmark).

The photograph of the display of 18/19 June 1976, taken by Dr D. A. R. Simmons of Milngavie, near Glasgow, was published on the cover of *Weather* (July, 1977); backed up by his account of the display, this photograph has been awarded the James Paton Memorial Prize for 1977.

TABLE II—ADDITIONAL REPORTS OF NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1976

Date—night of	Times UT	Notes	Station position		Time UT	Max. elev.	Limiting azimuths
						degrees	
7/8 June	2400	Colour photographs were taken showing Groningen silhouetted against the NLC.	53°N	06·5°E			
6/7 July	0030	Several concentrations of fine filament type formation NLC in NW and single patch also in NE—moving very slowly westwards.	53°N	06·5°E	0030	6	315–045

REVIEWS

Applied statistics in atmospheric science, Part A: Frequencies and curve fitting (*Developments in Atmospheric Science* 4*A*) by Oskar M. Essenwanger, 240 mm × 170 mm, pp. xiv + 402, *illus.* Elsevier Scientific Publishing Company, Amsterdam, The Netherlands, 1976. Price: $53.95, Dfl 140.00.

A new book on meteorological statistics is always something to look forward to, because there is a pressing need for texts which are more up to date in content and outlook than good old Brooks and Carruthers. Professor Essenwanger's book, which covers a good deal more ground than the title implies, does not quite live up to the promise of the early chapters. These are good, and provide clear and convincing accounts of topics which meteorologists cannot readily find elsewhere, but in the later sections, the discussion on time series analysis gives the impression that the author's extensive personal experience in the field of atmospheric turbulence has not extended to climatology. The chapter on factor analysis is not very satisfactory, but perhaps no worse than other accounts of this unsatisfactory subject. The extensive section on principal component analysis suggests that the author is out of touch with scientists at institutions such as the University of Wisconsin or the Meteorological Office, where principal component analysis is one of the tools of the trade. If these comments seem a little condescending, the author has stated his wish not to produce another text on theoretical statistics, but given this good intention, he might have done better to include only those topics in which each subject could be followed by a worked example drawn from his personal experience. The book would then have been more down to earth, and probably a good deal shorter. Still, it is good in parts, and should prove valuable to the reader who already knows how he intends to tackle his assignment, and is prepared to dip into the book for further information. With all its faults, a noteworthy addition to the literature on meteorological statistics.

J. M. CRADDOCK

The weather almanac (*second edition*), edited by J. A. Ruffner and F. E. Bair. 225 mm × 150 mm, pp. viii + 728, *illus.* Gale Research Co., Detroit, Michigan, U.S.A., 1977. Price: $25.

The first (1974) edition of this book was reviewed by P. G. F. Caton in the April 1977 issue of the *Meteorological Magazine*. For the second edition the editors have revised and updated the weather records of 108 selected cities from the United States and various other statistical tables. A chapter entitled 'Weather fundamentals' has been added, which is a fast-moving course in meteorology in no more than 40 pages including many diagrams and photographs. The section on air pollution has been largely rewritten and now includes more discussion of meteorological principles. The book continues of course to deal almost exclusively with the United States of America except for the 'Round-the-world weather' section.

R. P. W. LEWIS

OFFICIAL PUBLICATIONS

The following publications have been issued since the two series concerned were last referred to under this heading in the *Meteorological Magazine:*

Geophysical Memoirs

No. 120. Average temperatures, contour heights and winds at 30 millibars over the northern hemisphere. By R. A. Ebdon. (London, HMSO. £11.50.)

No. 121. Bumpiness in clear air and its relation to some synoptic-scale indices. By W. R. Sparks, B.Sc., S. G. Cornford, M.Sc., and J. K. Gibson, G.I.M.A. (London, HMSO. £3.75.)

Scientific Papers

No. 34. The Meteorological Office operational 10-level numerical weather prediction model (December 1975). By D. M. Burridge, Ph.D., and A. J. Gadd, Ph. D. (London, HMSO. £1.25.)

No. 35. A study of some aspects of the climate of the northern hemisphere in recent years. By D. J. Painting, B.Sc. (London, HMSO. 80p.)

No. 36. A computer-based model for design rainfall studies in the United Kingdom. By J. F. Keers, B.Sc. and P. Wescott. (London, HMSO. 85p.)

No. 37. The variability of long-duration rainfall over Great Britain. By R. C. Tabony, B.Sc. (London, HMSO. 85p.)

No. 38. The psychrometer coefficient of the wet-bulb thermometers used in the Meteorological Office Large Thermometer Screen. By C. K. Folland, B.Sc. (London, HMSO. £1.25.)

NOTES AND NEWS

Royal Meteorological Society Exhibition

The Royal Meteorological Society is mounting an exhibition in Bracknell College from 14 to 17 July 1978 inclusive which will be opened by Her Majesty the Queen. The Meteorological Office will be taking part in the exhibition together with about 80 other organizations. The exhibition will be divided into nine themes and the Office is proposing to contribute items in seven of these. Amongst the contributions from the Office will be a working automatic weather station, an operating Stratospheric Sounding Unit and a video display of the results from some experimental numerical forecasting models. The Central Forecasting Office will maintain a display of current analyses and prognoses in the entrance hall of the College.

International conference on 'Evolution of planetary atmospheres and climatology of the earth'

The Centre National d'Études Spatiales (CNES) is organizing an international conference on 'Evolution of planetary atmospheres and climatology of the earth' to be held at the Palais des expositions in Nice (France) from 16 to 20 October 1978.

The main topics will be: Comparative evolution of planetary atmospheres; Evolution of the earth's climates up to the present time; Physical mechanisms of the climate and modelling; Measurement and modelling prospects.

Those who are interested in the conference should contact

Centre National d'Études Spatiales,
Département des Affaires Universitaires,
18, Avenue Édouard-Belin,
31055 TOULOUSE CEDEX,
France.

HONOUR

We note with pleasure that Dr K. A. Browning, Senior Principal Scientific Officer at the Meteorological Office Radar Research Laboratory, Malvern was elected a Fellow of the Royal Society on 16 March. Dr Browning has made exceptional use of radar techniques, especially of Doppler radar, to elucidate the structure and evolution of precipitating cloud systems. Using radar and other sounding techniques and powerful new methods of meteorological analysis, he has been able to establish, for the first time, a comprehensive, self-consistent, quantitative description of the air motion in both frontal cloud systems and thunderstorms and to relate this to the distribution and intensity of rain and hail. He has also used the powerful radar at Malvern to gain new insight into the mechanisms of clear-air turbulence and the initiation of convection. Dr Browning's work is characterized by exceptional observational skill and physical insight and an unrivalled ability to analyse and synthesize large masses of complex observational data, to extract from them quickly the essential facts and to present them clearly as unique case studies which will serve as models for many years to come.

PROFESSOR P. A. SHEPPARD

With the passing of Professor P. A. Sheppard, C.B.E., F.R.S. on 22 December 1977, British meteorology lost one of its leading figures of the post-war era. Born in 1907, he graduated with first-class honours in physics at Bristol University in 1927 and joined the Meteorological Office as a junior professional assistant in 1929. His last professional appearance was at a meeting of the Physical Sub-committee of the Meteorological Research Committee held at Bracknell on 24 October 1977, only a few weeks before his death. He was therefore associated with the Meteorological Office from the beginning to the end of his career stretching over nearly half a century.

Soon after joining Kew Observatory he began to plan for the International Polar Year, 1932–33, which he spent as a member of a small British team that included J. M. Stagg and Angus Grinsted at Fort Rae in the North-west Territories of Canada and carried out research on atmospheric electricity. On his return he was posted to the Meteorological Office group at Porton headed by O. G. Sutton which was concerned with meteorological aspects of chemical warfare and there began his researches on turbulence and diffusion in the atmospheric boundary layer which were to become his main scientific interest for the next forty years.

Sheppard resigned from the Office in April 1939 on being appointed Reader in meteorology at Imperial College under Professor (later Sir David) Brunt but returned to the Office at the outbreak of war. For the first few months he was an instructor with Brunt at the Meteorological Office Training School but, for the remainder of the war, was heavily involved in the establishment of the radiosonde network and in co-ordinating upper-air observations derived from a variety of sources and techniques.

In 1945 he returned to Imperial College where he assisted Sir David Brunt in establishing the only fully-fledged university department of meteorology in the country, recruiting a group of young men each of whom was to become a leading authority in his own field. In a remarkably short time the department became internationally famous as a postgraduate centre of research and teaching, attracting students and senior research workers from all over the world. Here Sheppard, who succeeded Brunt to the professorship in 1952, played a very important role, not so much by his leadership in research, but as the most widely read and informed meteorologist of his day, whose penetrating criticisms, scholarly review articles and lucid lectures were of great value and influence.

From about 1957 onwards he became increasingly involved in many important activities outside the department where his breadth of knowledge and incisive mind showed to great advantage. He served the Royal Meteorological Society with great ability and devotion as Secretary, Editor and as President (1957–59). He was a stimulating and provocative member of any committee and an excellent chairman. He was a member of the Meteorological Research Committee from 1947 until his death and was Chairman from 1958 to 1968, a remarkable record for which he received the C.B.E. in 1963.

As Chairman of the Science Research Council's Space Policy and Grants Committee from 1965 to 1971, and vice-chairman of the ESRO Council, he played an important role in the formative years of European space research. But, sadly, the work-load and travelling put a heavy strain on his energies and took him away a great deal from his department which, with the departure or illness of several of its leading members, lost its former eminence. This must have been a worry to Sheppard, but he never lost his optimism, or his love of, and interest in, meteorology even during a long, debilitating illness which he endured with great fortitude and humour. It was during these last few years especially that I, and probably many others, came to realize that his bark was much worse than his bite and to appreciate his warm, human qualities. This makes his passing especially sad and leaves a gap that will be hard to fill.

B. J. MASON

THE METEOROLOGICAL MAGAZINE

NO. 1271 JUNE 1978 VOL. 107

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, and marked 'For Meteorological Magazine'.

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

Complete volumes of 'Meteorological Magazine' beginning with Volume 54 are now available in microfilm form from University Microfilms International, 18 Bedford Row, London WC1R 4EJ, England.

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1 monthly **Annual subscription £13.14 including postage**

Dd. 595890 K15 6/78

ISBN 0 11 724800 2
ISSN 0026–1149

Met.O.915
METEOROLOGICAL OFFICE

the meteorological magazine

JULY 1978 No 1272 Vol 107
Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.915

THE METEOROLOGICAL MAGAZINE

No. 1272, July 1978, Vol. 107

551.524.34(424 + 425)

A STATISTICAL STUDY OF THE LIKELY INFLUENCE OF SOME CAUSATIVE FACTORS ON THE TEMPERATURE CHANGES SINCE 1665

By M. K. MILES and P. B. GILDERSLEEVES
(Meteorological Office, Bracknell)

SUMMARY

An estimated hemispheric temperature anomaly based on smoothed central England temperatures has been produced. The multiple regression equation of this series with values of volcanic dust veil index (DVI), Wolf number and carbon dioxide content has been worked out for the whole period 1665–1974 and for a selection of epochs within this span of 310 years.

The study provides little or no confirmation of the cooling effect of volcanic dust shown by the data for the most recent 100 years. The results for the relation between hemispheric temperature and Wolf number are similarly contradictory.

The study does nothing either to contradict or to weaken the indication of warming due to carbon dioxide demonstrated by the data for the most recent 100 years.

INTRODUCTION

In an earlier paper Miles and Gildersleeves (1977) reported on a statistical study of the temperature changes over the last hundred years. From the point of view of such a study this period has the drawback that several of the quantities examined have just one maximum and one minimum and therefore a single coincidence could lead to an apparent strong association. For example, the temperature itself has low values over the first 30 or so years, then higher values apart from the last decade. The carbon dioxide curve has nearly this pattern and the amount of volcanic dust has nearly the opposite shape. The amount of sunspot activity also steadily increased from low values in the first 50 years to higher values in the second 50 years.

Neither the total effect of these three factors on the hemispheric temperature nor the size of their relative contributions is known with such certainty that one can assert categorically that their apparent association over this century is not due to coincidence.

In the period back to 1665 there are two or three periods of low volcanic activity and about the same number with high activity comparable to the period 1870–1910 as can be seen from Figure 1. Likewise the sunspot numbers show three main periods of high values and two of low values as can be seen

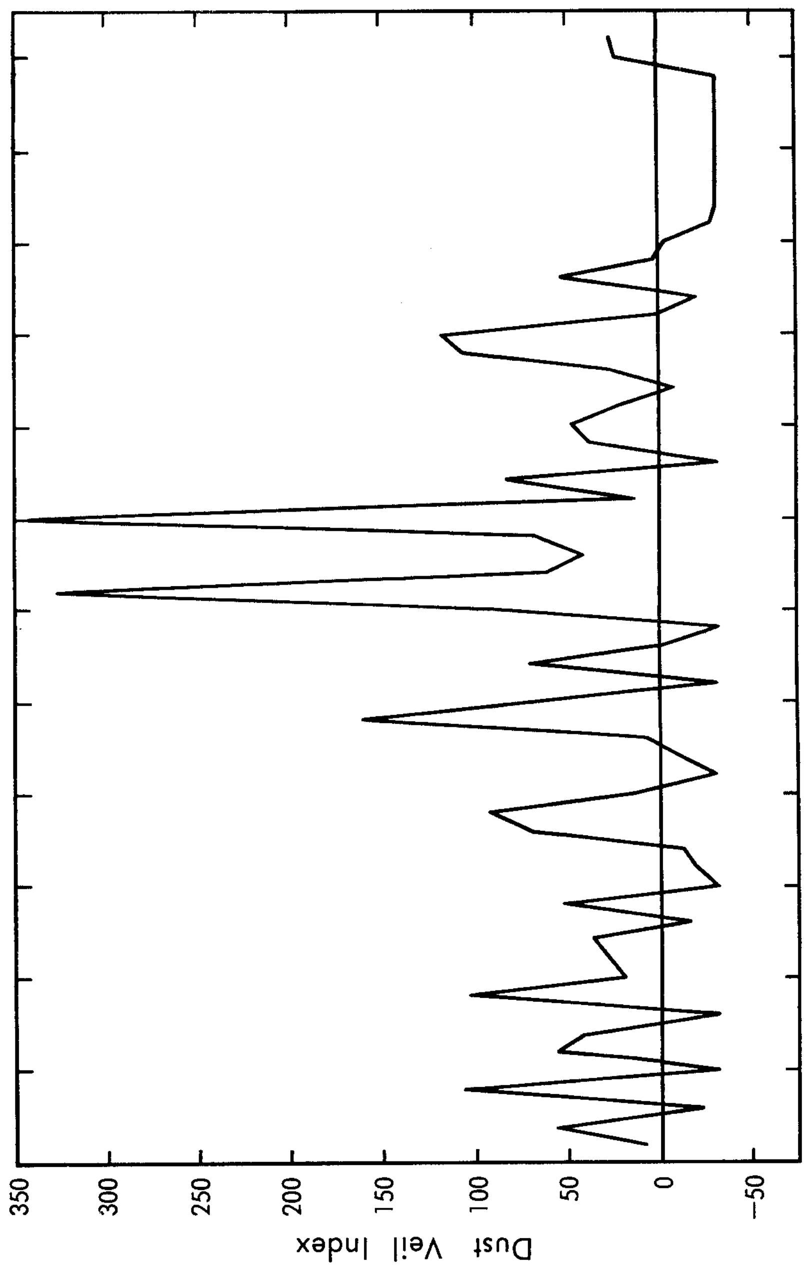

FIGURE 1—FIVE YEAR MEAN ANOMALIES OF DUST VEIL INDEX
Values are plotted against the first year of each five year period.

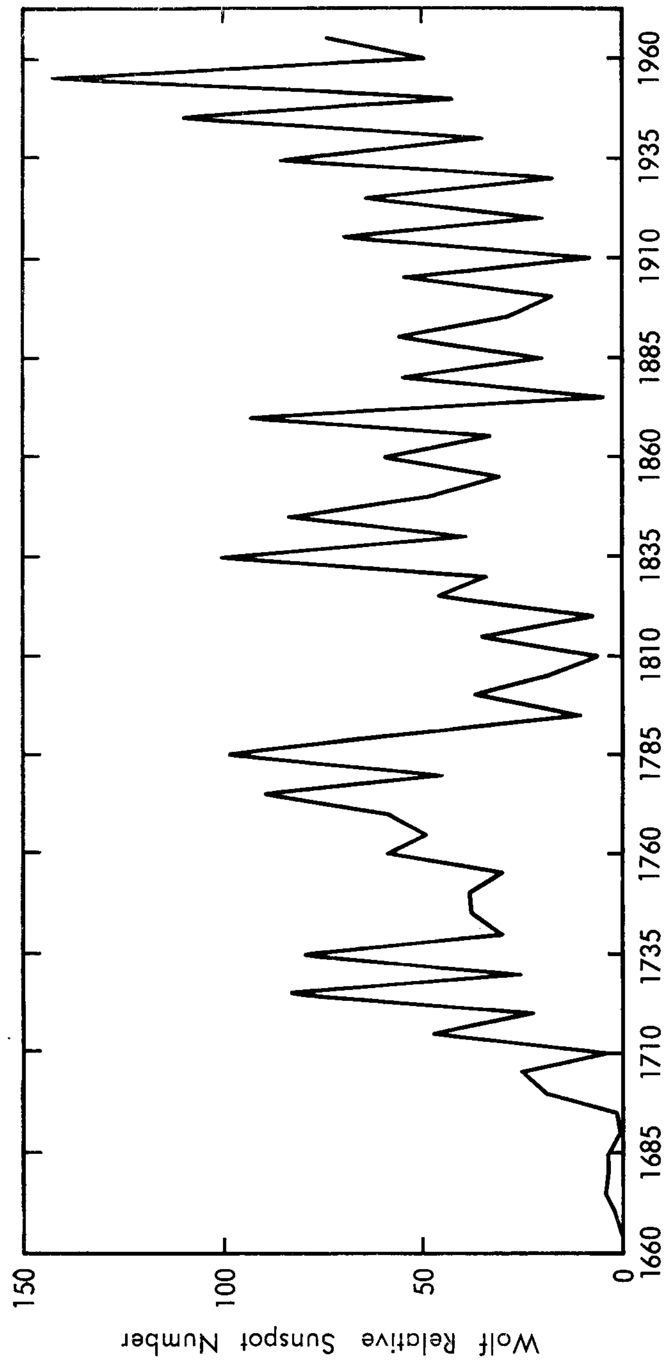

FIGURE 2—FIVE YEAR MEANS OF WOLF RELATIVE SUNSPOT NUMBERS
Values are plotted against the first year of each five year period.

from Figure 2. There is besides nearly 50 years of almost zero sunspot number—the now well-known Maunder Minimum which is dated 1650–1705. About the natural variations of the carbon dioxide content of the atmosphere in this time we know little, but it is thought unlikely (Bacastow and Keeling, 1972) that they were comparable with the increase which has accompanied increasing industrial activity in the late 19th and 20th centuries.

The three principal series of northern hemisphere temperatures—those due to Willett (1950), Mitchell (1961) and Budyko (1969)—all begin after 1870. There is a series compiled by Köppen (1914) and extended by Humphreys (1940) which goes back to 1750, and which has been used by Bray (1971) to study the effect of volcanic eruptions on temperature. The conclusion reached, namely that the temperature is lower than would be expected in the second year after major eruptions, has recently been quoted by Pollack and his fellow-workers (Pollack *et alii*, 1976; Baldwin *et alii*, 1976) in support of a theoretical model of radiative balance and stratospheric aerosol concentration. It is important therefore to consider how closely the Köppen series, based of necessity on a small number of observing stations mainly in temperate latitudes, represents the hemispheric temperature variations or whether it can be improved upon in any way.

TEMPERATURE SERIES USED IN THIS STUDY

For the short time when the Köppen series overlaps with the Mitchell–Budyko series (1870–1920) the correlation of the five year means is 0·16 compared with a value of 0·60 between the Mitchell–Budyko and Manley (1974) central England series for the same period. The relation of the Köppen series is greatly diminished by a very doubtful value for the year 1871, but nevertheless the relative value of the correlation indicates that the variations of the hemispheric temperature may be more closely represented by a single homogeneous series than by an assembly of stations some of which may be inhomogeneous.

With this in mind some further comparison of the hemispheric and central England temperatures was undertaken for the full period 1870–1969. The correlation of the five year means is 0·68 and the standard deviations are 0·20 K for the hemispheric temperature and 0·32 K for the central England temperature. Hence further smoothing of central England temperatures might be necessary to eliminate regional effects. Accordingly 10 year means of the central England temperature centred at the middle year of the five year means of the hemispheric series were formed, and these show a correlation coefficient over the 100 years of 0·81; their standard deviation is 0·25 K.

This suggests that a temperature regressed from the 10 year means of central England temperature might be a useful guide to the hemispheric temperature changes before 1870, but it must be remembered that these probably represent the temperature north of 30°N since the tropical oceans are scarcely represented at all.

A series has accordingly been formed from the regression relation

$$T_{\mathrm{hemi}} = 0{\cdot}62\, T_{\mathrm{CE}},$$

where T_{hemi} is the anomaly of the estimated 5 year mean hemispheric temperature and T_{CE} is the anomaly of the centred 10 year mean of central

England temperature, that is to say 10 years 1868–77 would be used to derive the hemispheric anomaly for the five years 1870–74. Both anomalies are with respect to the mean for the period 1870–1969, which for the central England series has been taken as 9·3 °C.

The values of this estimated series are shown in Figure 3, where the Köppen–Humphreys values are also plotted for comparison. The following comments may be appropriate.

(1) The main peaks and troughs in the two series occur nearly together; the 1870–74 minimum in the Köppen series is a notable exception, which, as was mentioned earlier, is largely due to a doubtful value for 1871.

(2) The standard deviation of the 5 year means of the estimated series is 0·17 K compared with 0·28 K for the Köppen series; the estimated series is nearer the standard deviation of 0·20 K shown by the Mitchell–Budyko series for 1870–1969.

Data used in the study

The five year means of temperature anomaly, dust veil index, Wolf number and carbon dioxide content used in the study are given in Table I.

The temperature anomalies are the estimated values described in the previous section. The dust veil index means are taken from Lamb (1970) with amendments as given by Lamb (1977) included. The Wolf number means are from Waldmeier (1961) for 1750 onwards and from Eddy (1976) before 1750. The carbon dioxide values are as used by Miles and Gildersleeves (1977) after 1870 and have been taken as constant at the 1870–74 value for the time back to 1665.

No attempt has been made to introduce an index of the ice because the earlier study showed that its effect is mainly a feedback one which enhances the temperature changes produced by other factors.

Method of procedure and results

The multiple regression scheme described by Miles and Gildersleeves (1977) for the previous study was used again. Six separate runs of this program covering different time periods were made and these are listed in Table II together with the correlation coefficients obtained.

The first two runs go back to the earliest date, 1665, differing only in the end time. Both show the Wolf number as having the strongest relation with temperature. This arises largely because the lowest temperatures occur at the time of the Maunder Minimum. The period of the Maunder Minimum is removed in runs 3 and 4 to see what the relation is like outside this remarkable period. As runs 4 and 5 show, it is a lot weaker and arises entirely from the last 100 years. The 155 years from 1715 to 1869 show no correlation between the variables at all.

These five runs also indicate that the negative correlation of temperature with volcanic dust arises almost entirely from the last 100 years. It might be argued that five year means are an inappropriate way of revealing this relationship since the dust from even strong eruptions may have largely fallen out within two to three years, but Lamb (1970) found high correlations with decadal means. There may also be a lag of several years in the atmospheric response to volcanic dust. The various studies do not agree sufficiently well on these points to make it worth while to enter the dust veil with a few years' lead in this study. Perhaps

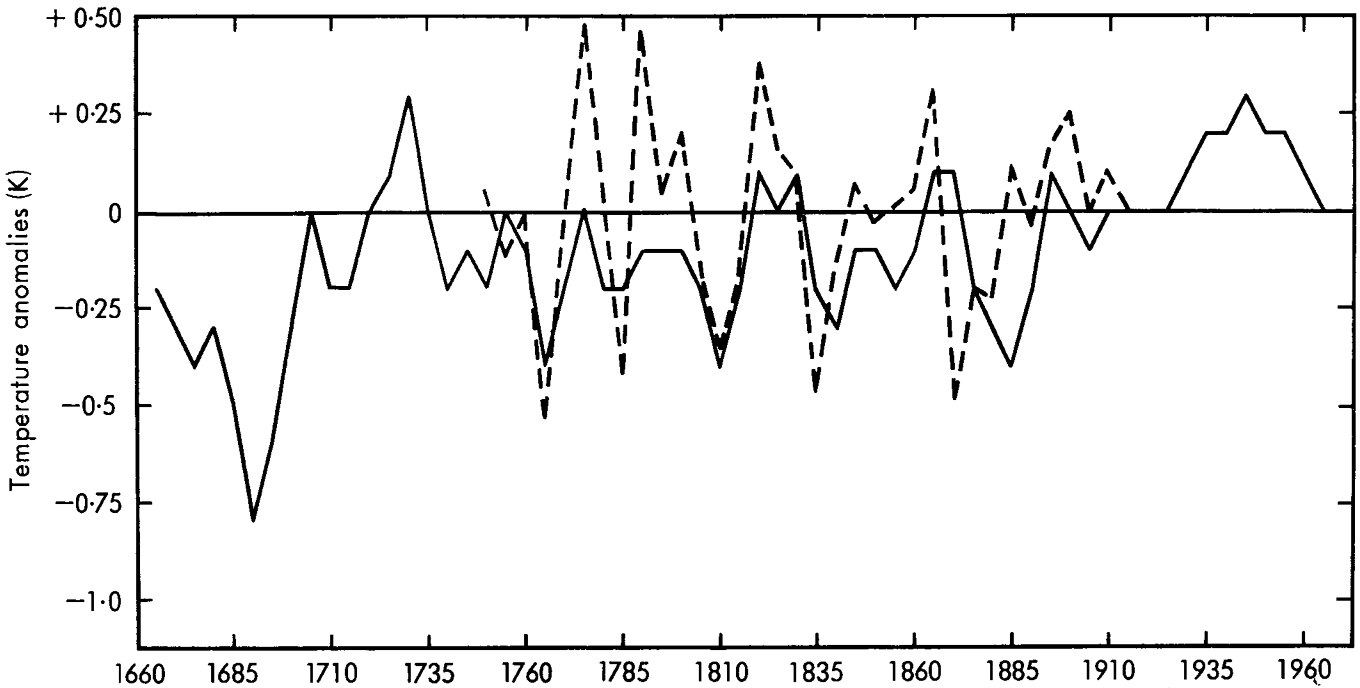

FIGURE 3—FIVE YEAR MEANS OF NORTHERN HEMISPHERE TEMPERATURE ANOMALIES

—— estimated from central England temperature
– – – derived from the Köppen–Humphreys temperature series
Values are plotted against the first year of each five year period.

TABLE I—FIVE YEAR MEANS OF TEMPERATURE ANOMALY, DUST VEIL INDEX, WOLF NUMBER AND CARBON DIOXIDE CONTENT

	Temp. anomaly *K*	DVI	Wolf No.	CO_2
1665–69	—0·2	7	0	—14
1670–74	—0·3	58	2	—14
1675–79	—0·4	—22	4	—14
1680–84	—0·3	108	3	—14
1685–89	—0·5	—32	3	—14
1690–94	—0·8	53	0	—14
1695–99	—0·6	39	1	—14
1700–04	—0·3	—32	18	—14
1705–09	0·0	103	25	—14
1710–14	—0·2	19	3	—14
1715–19	—0·2	26	47	—14
1720–24	0·0	30	22	—14
1725–29	0·1	—17	83	—14
1730–34	0·3	54	23	—14
1735–39	0·0	—32	79	—14
1740–44	—0·2	—20	31	—14
1745–49	—0·1	—14	43	—14
1750–54	—0·2	70	44	—14
1755–59	0·0	92	31	—14
1760–64	—0·1	17	58	—14
1765–69	—0·4	—32	49	—14
1770–74	—0·2	—10	63	—14
1775–79	0·0	7	80	—14
1780–84	—0·2	162	45	—14
1785–89	—0·2	58	98	—14
1790–94	—0·1	—32	61	—14
1795–99	—0·1	72	11	—14
1800–04	—0·1	4	37	—14
1805–09	—0·2	—32	18	—14
1810–14	—0·4	88	7	—14
1815–19	—0·2	325	35	—14
1820–24	0·1	61	7	—14
1825–29	0·0	36	46	—14
1830–34	0·1	68	34	—14
1835–39	—0·2	343	101	—14
1840–44	—0·3	13	30	—14
1845–49	—0·1	81	84	—14
1850–54	—0·1	—32	49	—14
1855–59	—0·2	38	36	—14
1860–64	—0·1	48	65	—14
1865–69	0·1	24	33	—14
1870–74	0·1	—8	93	—14
1875–79	—0·2	28	10	—13
1880–84	—0·3	108	55	—12
1885–89	—0·4	118	21	—11
1890–94	—0·2	2	56	—10
1895–99	0·1	—20	34	—9
1900–04	0·0	53	17	—8
1905–09	—0·1	4	55	—7
1910–14	0·0	—2	8	—6
1915–19	0·0	—29	70	—4
1920–24	0·0	—32	20	—3
1925–29	0·0	—32	64	—1
1930–34	0·1	—32	17	1
1935–39	0·2	—32	86	3
1940–44	0·2	—32	35	6
1945–49	0·3	—32	110	8
1950–54	0·2	—32	42	11
1955–59	0·2	—32	143	14
1960–64	0·1	24	49	17
1965–69	0·0	26	74	21

Temperature anomalies are the estimated values described in the foregoing text. Dust veil index (DVI) means are taken from Lamb (1970) as amended by Lamb (1977). The Wolf number means are from Waldmeier (1961) for 1750 onwards and from Eddy (1976) for the years before 1750. The carbon dioxide values are as used by Miles and Gildersleeves (1977) after 1870 and have been taken as constant at the 1870–74 level from 1869 back to 1665.

TABLE II—CORRELATION COEFFICIENTS BETWEEN THE TIME SERIES USED

	Temperature	DVI	Wolf No.
Run 1 (1665–1969)			
DVI	—0·23		
Wolf No.	+0·44	—0·05	
CO_2	+0·49	—0·30	+0·35
Run 2 (1665–1869)			
DVI	+0·01		
Wolf No.	+0·37	+0·14	
CO_2	(not entered—constant value throughout)		
Run 3 (1715–1969)			
DVI	—0·36		
Wolf No.	+0·23	—0·06	
CO_2	+0·52	—0·32	+0·29
Run 4 (1715–1869)			
DVI	—0·12		
Wolf No.	—0·03	+0·10	
Run 5 (1870–1969)			
DVI	—0·80		
Wolf No.	+0·44	—0·33	
CO_2	+0·61	—0·44	+0·41
Run 6 (1750–1919)			
DVI	—0·24 (—0·26)		
Wolf No.	+0·05 (—0·26)	+0·09	
CO_2	+0·20 (+0·14)	—0·23	—0·11

Bracketed values in Run 6 refer to the Köppen–Humphreys temperature series.

the most interesting feature of these five runs is the consistently high correlation between CO_2 and temperature whenever CO_2 was included.

Run 6 covers the period of the Köppen–Humphreys series and the figures in brackets are for their temperature series. The correlation with volcanic dust is low with both series, which suggests that Bray's (1971) conclusion should be accepted with caution. The values of the temperature change are exaggerated by the larger standard deviation of this series. The Wolf number correlation is negligible for the estimated temperature series and has a negative value with a low statistical significance for the Köppen–Humphreys series, whereas in all other runs it has shown a positive correlation with temperature.

FURTHER DISCUSSION OF RESULTS

Table III shows the coefficients of the various terms in the multiple regression equations for the six runs. The multiple correlation coefficients given in the last column suggest that the variance in the temperature curve can be best explained for the past 100 years and least well explained for the middle period 1715–1869. In part this may be due to the temperature series being a better approximation to the true hemispheric temperature variations for the last 100 years than in the previous 150 years. The improved correlation when the earliest 50 years are brought in (run 2 compared with run 4) thus remains puzzling and leaves one wondering whether there is any physical association between the very low temperatures during this time and the very low sunspot activity.

TABLE III—COEFFICIENTS OF VARIOUS TIME SERIES IN THE MULTIPLE REGRESSION EQUATIONS (THOSE MARKED WITH AN ASTERISK ARE NON-SIGNIFICANT)

Run No.	DVI	Wolf No.	CO_2	Intercept	*N*	*R*
1 (1665–1969)	—0·0003	0·0021	0·0086	—0·1023	61	0·58
2 (1665–1869)	—0·0001*	0·0026	—	—0·2629	41	0·37
3 (1715–1969)	—0·0005	0·0006	0·0079	—0·0007	51	0·56
4 (1715–1869)	—0·0002*	—0·0002*	0*	—0·1032	31	0
5 (1870–1969)	—0·0025	0·0006	0·0049	—0·0088	20	0·86
6 (1750–1919)	—0·0003	0·0005	0·0080	—0·0018	34	0·28
	(—0·0007)	(—0·0023)	(0·0058)	(+0·1376)	34	0·35

N is the number of observations and *R* the multiple regression coefficient. Bracketed values in Run 6 refer to the Köppen–Humphreys temperature series.

TABLE IV—TEMPERATURE CHANGES ASSOCIATED WITH GIVEN CHANGES (Δ) IN THE VARIOUS FACTORS IN THE MULTIPLE REGRESSION EQUATION

Run	Δ	DVI Effect on temperature *kelvins*	Δ	Wolf No. Effect on temperature *kelvins*	Δ	CO_2 (ppm) Effect on temperature *kelvins*
1	375	—0·11	143	+0·30	35	+0·30
2	—	—	101	+0·26	—	—
3	375	—0·19	136	+0·08	35	+0·28
4	—	—	—	—	—	—
5	150	—0·38	135	+0·08	35	+0·18
6	375	—0·13	94	—	10	+0·08
		(—0·26)		(—0·22)		(+0·06)

Bracketed values in Run 6 refer to the Köppen–Humphreys temperature series.

Table IV contains the estimates of the contribution to temperature change attributed to the various factors in the analysis.

The contribution of volcanic dust for a change of −150 units (that is to say the change from the 1880s to the 1930s) varies from +0·05 K to +0·38 K (using only the significant values). The larger value derives from the last 100 years while the lower value comes from the whole period. The studies by Pollack *et alii* (loc. cit.) and their application by Miles and Gildersleeves (1978) suggest that to depress the five year mean temperature by from 0·2 to 0·3 K, two successive five year periods with a high DVI, such as 1880–84 and 1885–89 are required. In the period 1715–1869 four such periods can be recognized. They are listed in Table V with the observed temperature anomaly and the depression below the prevailing 50 year average.

TABLE V—TEMPERATURE ANOMALIES FOR DECADES WITH MAINTAINED HIGH DVI

	Mean temperature anomaly *kelvins*	Depression below 50 year mean *kelvins*
1750–59	—0·10	—0·01
1780–89	—0·20	—0·04
1810–19	—0·30	—0·19
1830–39	—0·05	+0·08

The period 1735–49 with very low DVI had a mean temperature slightly below the prevailing mean. Another period 1765–79 with very low DVI was also below the prevailing mean. The effect of volcanic dust appears therefore to be small, say less than 0·1 to 0·2 K for major series of eruptions, or variable as between different eruptions, which is a possibility raised by recent studies by Pollack *et alii* (loc. cit.).

The sunspot contribution for the change in the mean value of the Wolf number of about 50 from the early 20th century to the epoch 1935–60 varies from −0·1 to +0·1 K. The effect of a Wolf number of nearly zero during the Maunder Minimum cannot therefore be much more than 0·1 K above or below the general level. This does not of course apply if the complete absence of spots means a totally different radiation regime as Eddy (1976) has claimed.

The total carbon dioxide contribution from runs going up to 1969 varies from +0·18 K to +0·30 K. This range, assuming a linear increase of the effect with CO_2 concentration, corresponds to a warming of between 1·6 and 2·6 K for a doubling of the concentration from its mean value of 305 parts per million (ppm) or between 1·3 and 2·1 K if the effect is proportional to the square root of the CO_2 concentration. This is rather less than the value of 2·9 K computed by Manabe and Wetherald (1976) but the results from a regression equation would tend to lie below the true value. Between 1740 and 1869, and 1870 and 1969, there is a marked change in the linear trend of temperature, changing from 0·1 K/100 years in the earlier period to 0·4 K/100 years in the later one. This change is mirrored very closely by the change in CO_2 (Table I) and this visual impression is confirmed by inspection of the correlation coefficients (Table II) particularly for runs 1 and 3.

Figure 4 shows the curve of predicted temperature anomalies using the regression equation obtained from run 1 and it can be seen that this broad pattern of temperature change is well fitted by the equation. Noting that the change between 1870 and 1969 in CO_2 concentration is 35 ppm and that the average change in Wolf number over the same period is approximately 50 and using the coefficients for run 1 in Table III, 75 per cent of the rise in temperature is attributed to changes in CO_2 and 25 per cent to changes in the Wolf number.

Conclusions

The extension of the period examined back to 1715 provides little or no confirmation of a cooling effect due to volcanic eruptions indicated by the period 1870–1969. The data do not appear to be good enough to enable a firm conclusion, or one that applies to all volcanic episodes, to be reached.

This period 1715–1969 also provides somewhat contradictory indications about the relation between Wolf number and temperature. They appear not to be related for the period 1715–1869 and the small positive contribution after 1870 (see Table IV, run 5) can be as well explained by the effects of volcanic dust or CO_2 or both. From the Köppen–Humphreys data for 1750–1919 there is a negative relation of low statistical significance.

The addition of the period 1665–1715 appears to give some confirmation to the positive relation between Wolf number and temperature shown in the modern period, but even so would imply a depression of no more than 0·1–0·2 K during the time of zero sunspots unless there was at that time a totally different relation between radiation and sunspot number than otherwise prevails. The carbon dioxide effect is the one which emerges most consistently, and provides the best explanation of the enhanced linear trend after 1870.

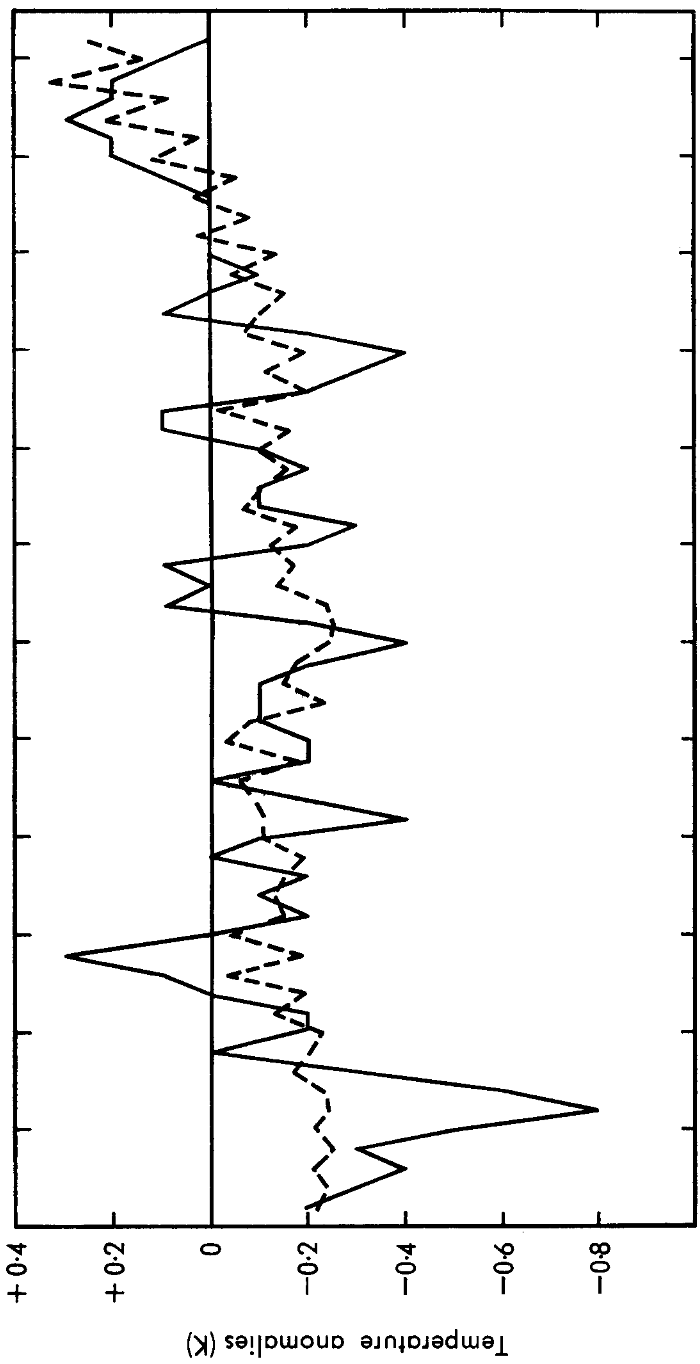

FIGURE 4—ESTIMATED AND PREDICTED FIVE YEAR MEAN TEMPERATURE ANOMALIES 1665–1969

—— estimated from regression
– – – predicted from run 1
Values are plotted against the first year of each five year period.

References

BACASTOW, R. and KEELING, C. D. 1972 Atmospheric carbon dioxide and radiocarbon in the natural carbon cycle: II. Changes from AD 1700 to AD 2070 deduced from a geochemical model. Washington, DC, US Atomic Energy Commission. Brookhaven Symposium on Biology, Upton, NY, 1972, Proceeding: Carbon and the biosphere. Woodwell, G. M. and Pecan, Erene V. (editors), Washington, DC, pp. 86–135.

BALDWIN, BETTY, POLLACK, J. B., SUMMERS, AUDREY, TOON, O. B., SAGAN, C. and VAN CAMP, W. 1976 Stratopheric aerosols and climatic change. *Nature*, **263**, pp. 551–555.

BRAY, J. R. 1971 Climatic change and atmospheric pollution. *Proc NZ Ecol Soc, Wellington*, **18**, pp. 38–41.

BUDYKO, M. I. 1969 The effect of solar radiation variations on the climate of the Earth. *Tellus*, **21**, pp. 611–669.

EDDY, J. A. 1976 The Maunder Minimum. *Science*, **192**, pp. 1189–1202.

HUMPHREYS, W. J. 1940 Physics of the air. New York and London, McGraw-Hill.

KÖPPEN, W. 1914 Lufttemperaturen, Sonnenflecke und Vulkanausbrüche. *Met Zeits, Braunschweig*, **31**, pp. 305–328.

LAMB, H. H. 1970 Volcanic dust in the atmosphere; with a chronology and assessment of its meteorological significance. *Philos Trans R Soc*, A, **266**, pp. 425–553.

1977 Supplementary Volcanic Dust Veil Index assessments. *Climatic Monitor*, **6**, pp. 57–67.

MANLEY, G. 1974 Central England temperatures: monthly means 1659 to 1973. *Q J R Met Soc*, **100**, pp. 389–405.

MILES, M. K. and GILDERSLEEVES, P. B. 1977 A statistical study of the likely causative factors in the climatic fluctuations of the last 100 years. *Met Mag*, **106**, pp. 314–322.

1978 Volcanic dust and changes in northern hemisphere temperature. *Nature*, **272**, pp. 735–736.

MITCHELL, J. M. 1961 Recent secular changes of global temperature. *Annal New York Acad Sci*, **95**, pp. 235–250

POLLACK, J. B. TOON, O. B., SAGAN, C., SUMMERS, AUDREY, BALDWIN, BETTY and VAN CAMP, W. 1976 Volcanic explosions and climatic change: A theoretical assessment. *J Geophys Res*, **81**, pp. 1071–1083.

WALDMEIER, M. 1961 The sunspot-activity in the years 1610–1960. Zurich, Schulthess & Co.

WILLETT, H. C. 1950 Temperature trends of the past century. *Cent Proc R Met Soc*, pp. 195–206.

551.507.362.2:551.576.2:77

A GUIDE TO SATELLITE PICTURE ANALYSIS

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SUMMARY

The satellite picture taken by NOAA 5 in orbit 851 on 6 October 1976 showed many synoptic features. An attempt is made to explain how to identify these features and to incorporate them into the analysis of charts in common use in the Meteorological Office.

Many meteorological offices are receiving satellite pictures directly from Bracknell which the forecasting staff at these offices analyse locally. Other meteorological offices are only receiving nephanalyses, which are freehand analyses of cloud structure and other features of synoptic importance, produced by an analyst at the Central Forecasting Office (CFO) at Bracknell. On 6 October 1976, pictures from NOAA 5, orbit 851, showed many features which are of interest to both surface and upper-air analysts. Reproduced on the following pages are the visual satellite photograph (Plate I), the nephananalysis (Figure 1), the surface plus thickness chart, and the 500 mb chart for 12 GMT on 6 October 1976 (Figures 2 and 3). The various areas of interest that will be discussed are annotated on the nephanalysis for easy reference.

The cold front 'V' may be positioned on the surface chart by inspection. Active cold fronts (ana-fronts) are positioned to the rear edge of the cloud band, whereas weak, slow-moving cold fronts (kata-fronts) are positioned to the forward edge. Cold fronts also indicate a zone of strong baroclinicity, and thickness lines are commonly closely packed on the poleward side of the cold front cloud band. Jet streams are often associated with cold fronts and are located to the poleward side of the cloud bands. They can often be accurately positioned by an abrupt boundary on the poleward side of the cirrus cloud: see position 'W'. Because of the elevation of the sun this cirrus edge frequently casts a shadow on the lower cloud to the poleward side: see positions 'V' and 'W'.

On infra-red satellite pictures jet-stream cirrus can often be seen as a bright, white, and long, narrow band. Trailing cold fronts often have wave development, and areas of potential wave development are frequently associated with 'comma clouds': see positions 'X'. These comma clouds are usually observed in areas of maximum positive vorticity advection (PVA), and are the result of moving vorticity centres to the rear of a polar front. Because of the ascent of air in the PVA areas there is usually an area of subsidence ahead of the comma cloud seen as a clear area. When the comma cloud moves to within about 350 n. mile of a frontal band, wave development can be expected. As a cloud pattern associated with vorticity approaches a front, the frontal cloud band broadens and becomes more concave-shaped (to the cold side), and cirrus cloud can often be seen streaming ahead of the wave. The surface position of the wave is under the bulge close to where the curvature of the rear edge of the frontal cloud band changes from concave to convex (at position 'Y'). Over the developing wave the thickness lines curve anticyclonically, with the thermal jet located just northwards

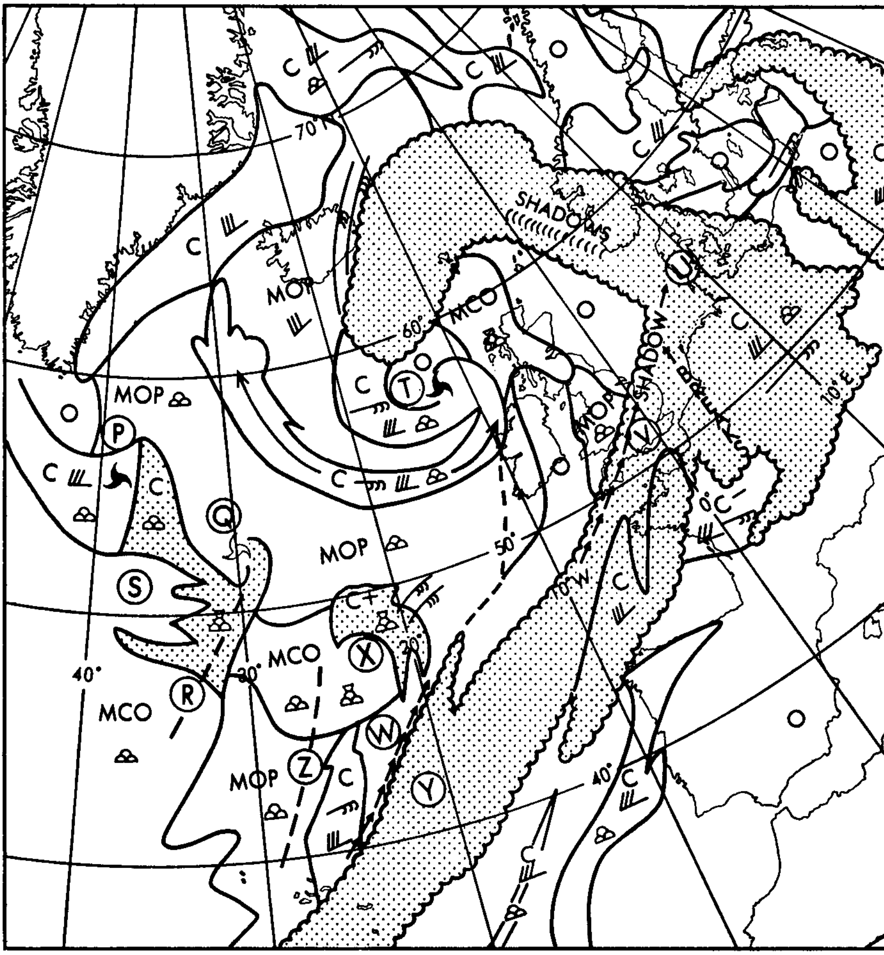

FIGURE 1—NEPHANALYSIS FOR 12 GMT ON 6 OCTOBER 1976

of the wave tip. Areas of maximum vorticity often occur just ahead of the 500 mb trough, and in satellite pictures the maximum vorticity is denoted by the comma cloud (PVA maximum). The 500 mb trough is therefore placed just behind the comma cloud as shown by 'Z'.

The area 'U' on the nephanalysis shows a cloud band running northwards and towards the vorticity centre and marks the position of the occlusion, while to the south is a warm sector. The cloud over the occlusion is lower and more lumpy than that over the warm sector, which is cirriform. This cloud change, which is sometimes enhanced on the satellite pictures by a shadow cast from the high cloud over the warm sector on to the lower cloud over the occlusion, denotes the continuation of the jet stream from the rear of the cold front. The point of occlusion should be placed just to the equatorial side of the demarcation line between the types of cloud, but the warm front cannot be located from

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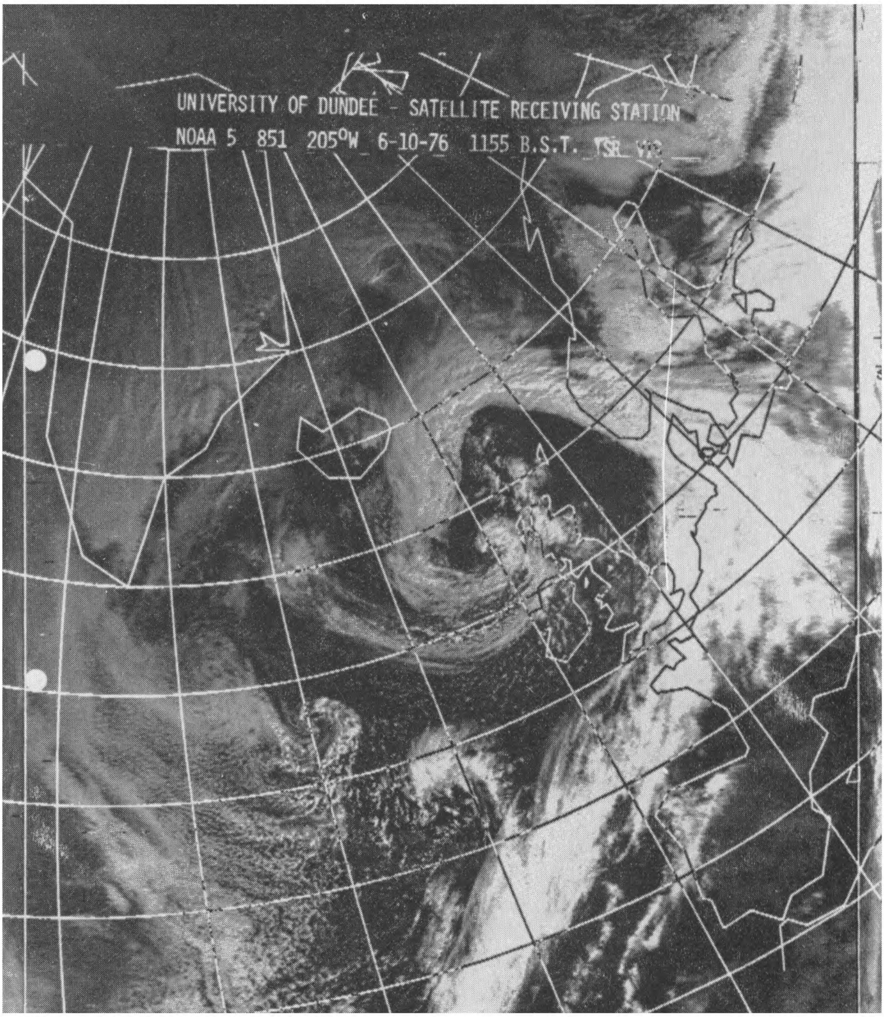

Photograph by the Department of Electronics and Electrical Engineering, Dundee University

PLATE I—PICTURE IN VISIBLE LIGHT FROM NOAA 5 AT 1055 GMT ON 6 OCTOBER 1976

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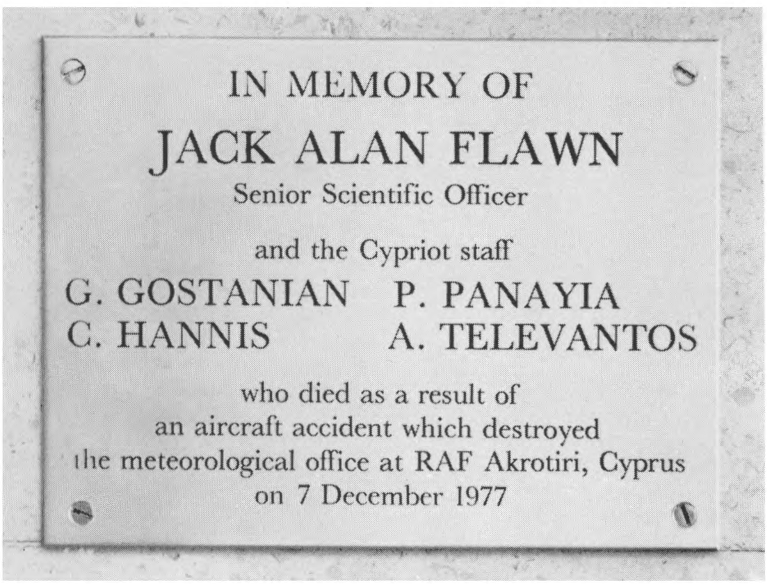

PLATE II—MEMORIAL PLAQUE IN THE ENTRANCE HALL OF THE METEOROLOGICAL OFFICE MAIN HEADQUARTERS BUILDING IN BRACKNELL

(See page 223.)

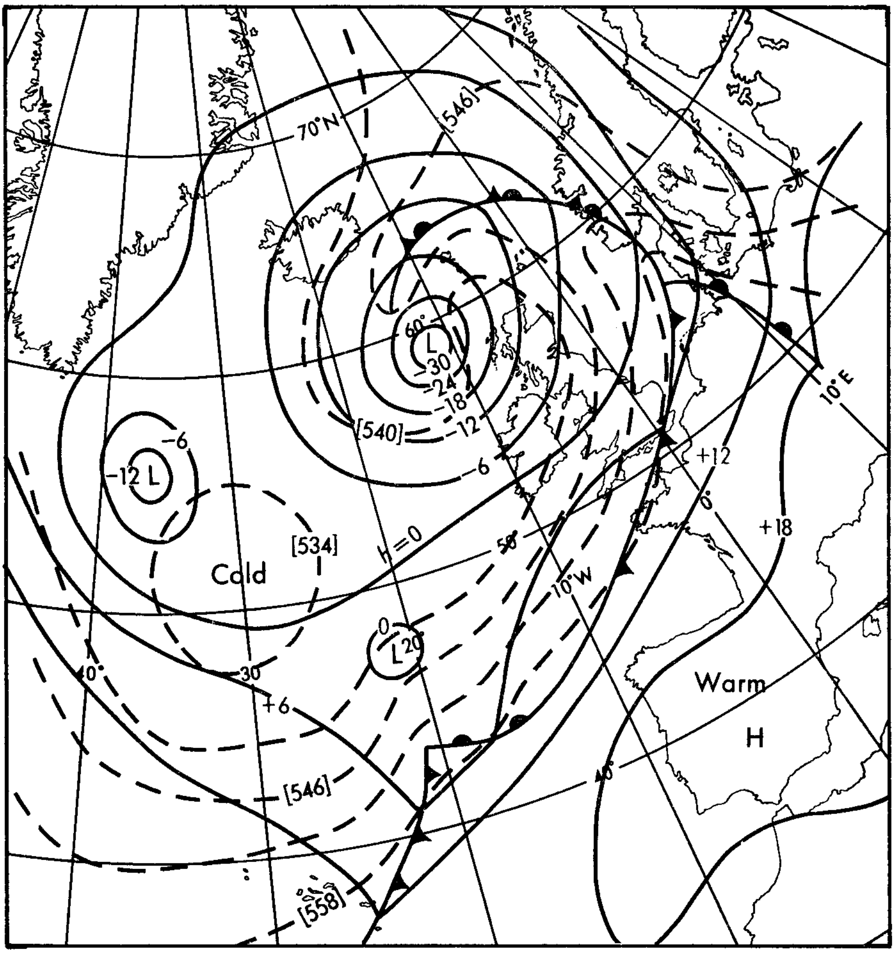

FIGURE 2—1000 mb HEIGHT AND 1000–500 mb THICKNESS CHART FOR 12 GMT ON 6 OCTOBER 1976

satellite pictures owing to the extensive cirrus shield ahead of it. Along the occlusion there is pronounced thermal ridging which has penetrated almost to the vortex centre. Warm sectors are usually homogeneous and there are very few thickness lines over them. To the rear of the occlusion there is a large clear area, which is caused by subsidence, and usually the more active and quickly moving the occlusion the larger the clear area.

The area marked 'T' on the nephanalysis shows a vorticity centre entering the dissipating stage. There are four stages in vorticity development that are discernible from satellite pictures. There is the comma cloud stage as seen in area 'X', and then, as the wave on a cold front develops, the curvature of the cloud bulge becomes more pronounced. The rear edge of the high cloud becomes more concave, and an area of lower thinner cloud appears along the rear edge of the wave. Rapid intensification of the circulation begins at about this time. In the

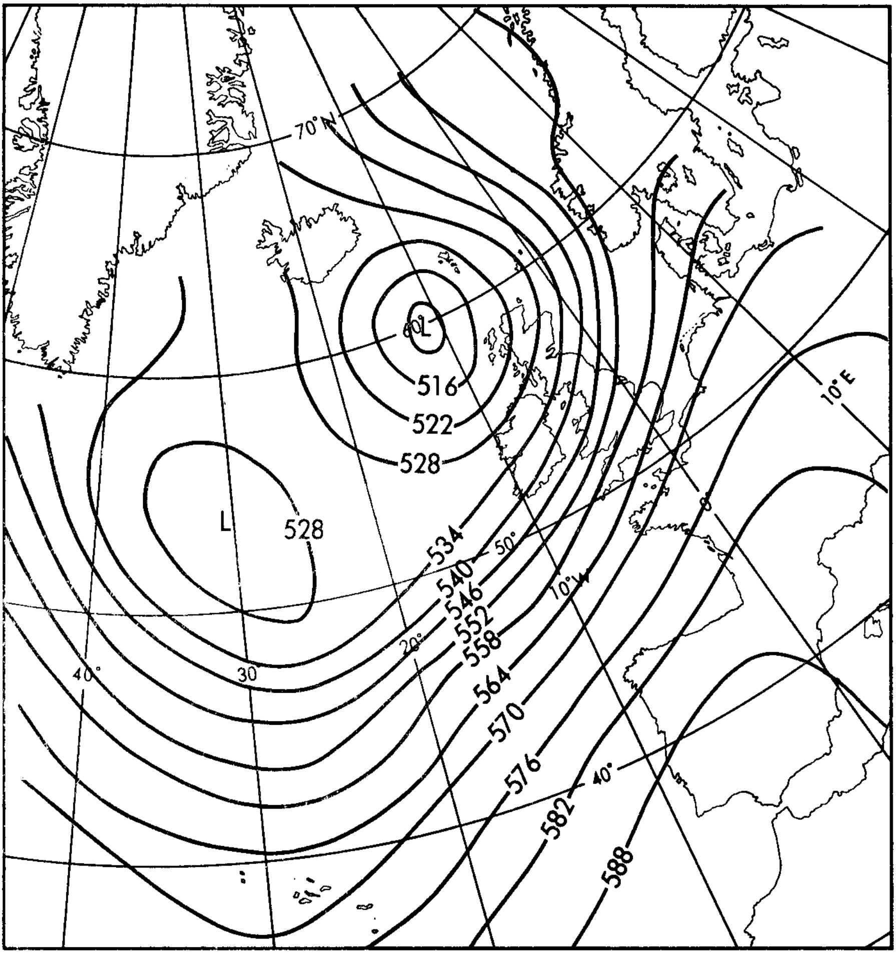

FIGURE 3—500 mb CHART FOR 12 GMT ON 6 OCTOBER 1976
Isopleths are labelled in geopotential decametres.

occluding stage the cloud begins to take on a spiral pattern and a clear or dry slot begins to form behind the front. In the mature stage the development has reached its maximum and the clear slot extends into the centre of the vortex. At this stage the vortex centre and the centres at the surface and in the mid troposphere are nearly coincident owing to the minimum tilt of the pressure centres with height. The dissipating stage is indicated where the vortex bands become fragmented and are mainly of medium- or low-level cumuliform and stratiform clouds. The frontal cloud band also becomes separated from the vortex centre. This pattern is usually associated with a 500 mb centre and a dissipating surface low.

In area 'S' on the nephanalysis polar air is moving southwards towards warmer seas. Cumulus humilis clouds will initially form in narrow lines at low levels, and these lines will closely approximate to the surface wind direction. When these clouds develop into 'open cells' they become arranged parallel to the vertical wind shear though the cloud layer and are thus closely aligned with the thermal wind. Open cells denote deep convection and are associated with cyclonic flow, whereas 'closed cells' occur more often in anticyclonic flow. The curvature of the open cells indicates a thermal trough along 'R' centred on a thermal low as shown by the well-defined thermal vortex at 'Q'.

The vortex seen at 'P' is mainly of low-level cloud and suggests a surface low at this position. Also a surface low at 'P' together with a thermal low at 'Q' suggests that there must be a 500 mb low close to 'Q'.

This particular case shows how the satellite picture and the nephanalysis derived from it can aid the forecaster in analysing both the surface and upper-air charts. More detailed reading can be found in *WMO Technical Note* No. 124 and *ESSA Technical Report* NESC 51.

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CO-OPERATING OBSERVERS AND THE CLIMATOLOGICAL NETWORK

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SUMMARY

The origins and development of the United Kingdom Climatological Network are briefly described and the very large contribution made by non-professional observers is emphasized.

INTRODUCTION

The UK Climatological Network is in many ways a remarkable institution. In an age when our observational armoury includes satellites, radar and sophisticated automatic sampling and recording devices, the basic measurements at Network stations are still made with quite simple instruments; and despite the widespread modern trends for increased specialism and for services to be provided by the State, almost 90 per cent of Network stations are maintained by non-professional observers. These facts appear to suggest that the organization has simply failed to move with the times, but paradoxically the simple approach and the non-professional co-operation thereby acceptable, are the very reasons why the Network is so effective.

The purpose of a climatological observing network is to provide information from which the climatology of the country may be determined. It is essential for the observations to be made regularly to a common high standard, and for the spacing of the observing stations to be close enough to represent adequately the variations of climate to be found over different types of terrain in all parts of the country. But the basic observations of temperature, rainfall, sunshine, pressure, wind, humidity, visibility, weather and so on can be made by eye with the aid of simple instruments; if human observers are available in the right places, there is no need for complicated and expensive equipment. The UK Climatological Network has therefore been organized in a particularly cost-effective way by tapping the large reservoir of amateur interest in the weather and channelling the flow of information through professional filters. Without the voluntary stations, it would be impossible to achieve the required network density; without the professional co-ordination, the necessary uniform standards would not be attained. The two components are complementary to each other and in combination they make the Network an alloy of great strength.

Origins of the Network

With the invention of instruments such as the thermometer, barometer and rain-gauge, it became possible during the 17th century to make simple meteorological measurements, and the scientific curiosity of an age in which the Royal Society was founded led a number of gentlemen to make regular observations and to compare notes. From these initially haphazard exchanges, by the early half of the 19th century a strong tradition of amateur interest in weather observing had developed and regular observing routines had been established at certain scientific institutions. The value of this work gradually came to be accepted by a wider public, and by the late 1870s, a few municipalities had set up their own local weather observing stations, as had several schools and colleges.

Before this, however, the electric telegraph had been invented in 1844, and this offered a means of collecting weather data within a few hours. The first daily weather report was published in a newspaper only four years later, primarily for the benefit of farmers. At that time, most of the telegraph lines were associated with the railways, and in 1849 the railway companies were persuaded to contribute regular weather observations for publication; James Glaisher travelled the country to organize a synoptic weather reporting network and to train railway staff as observers. When the Meteorological Department of the Board of Trade was formed in 1855 under Admiral FitzRoy (becoming the Meteorological Office in 1863), the safety of life at sea was the major concern; with the co-operation of the coastguard service, further telegraphic observing stations were organized as an integral part of a new storm warning service for inshore shipping.

It may be said that the UK Climatological Network formally came into existence in 1884 when the *Monthly Weather Report* was first published, and from the outset we may distinguish the three strands that were brought together. Firstly there were the Co-operating Observers, both private and those at institutions or municipalities, whose contribution was voluntary; these people shared a common interest in the weather, and in many cases this interest amounted to a spirit of dedication that has enriched the network throughout its history. The second strand was formed by some of the Auxiliary Observers who had been recruited for the synoptic network; most of these observers were employed in jobs that were in some way weather-related, and their observations were made whilst on duty. At least one railway observing station (Hawes Junction) contributed to the 1884 Report, as did a number of coastguard stations. Finally there was the Meteorological Office itself which played the key organizational role that brought the Network into existence and which laid down, and by inspection maintained, the necessary uniform standards for observing.

Development of the Network

The growth of the Network from its inception to the present day is shown in Table I. It is remarkable that roughly a quarter of the stations that contributed to the first *Monthly Weather Report* in 1884 are still submitting returns 94 years later.

These 17 stations are:

Aberdeen	Hastings	Rothamsted
Armagh	Liverpool (Bidston)	Scarborough
Cambridge	Marlborough	Scilly (St Mary's)
Douglas	Nairn	Stonyhurst
Durham	Oxford	York
Falmouth	Plymouth	

A further 13 stations which are still reporting joined the Network before the turn of the Century:

Braemar	Glenlee	Sheffield
Cockle Park	Lowestoft	Southport
Colwyn Bay	Marchmont	Torquay
Eastbourne	Margate	
Fort Augustus	Rhyl	

TABLE I—THE UK CLIMATOLOGICAL NETWORK

Year	Met. Office stations	Auxiliary synoptic stations	Co-operative climatological stations	Total
1884	1	29	36	66
1890	1	30	46	77
1895	1	30	47	78
1900	1	25	48	74
1905	1	26	179	206
1910	3	30	209	242
1914	4	31	304	339
1920	20	26	274	320
1925	20	27	289	336
1930	22	27	298	347
1935	25	24	316	365
1938	25	25	313	363
1946	84	20	324	428
1950	77	23	347	447
1955	80	24	393	497
1959	73	25	453	551
1965	71	48	473	592
1970	73	57	526	656
1975	72	59	511	642
1977	69	56	499	624

Notes

1. Met. Office stations include outstations and observatories.
2. Co-operating stations include Health Resort and Agro-meteorological stations.
3. Stations in Southern Ireland were included in the Network until the Second World War, i.e. in the above Table for all years to 1938.
4. Figures refer to 31 December in each year.

As may be seen from the above lists, a number of municipal authorities had joined the Network before 1900. Sensing an increasing awareness of the advertising value of references in the national press to weather at the resorts, the Meteorological Office decided in 1912 to introduce the Health Resort scheme. Local authorities were encouraged to set up climatological stations which would be inspected annually to ensure that common high standards of observing were maintained; in exchange for submission of the normal climatological returns, the Office undertook to accept evening telegrams from the resorts and from these to prepare a daily bulletin of approved readings for the Press. Except that since 1976 the evening reports have been collected by telephone, the scheme still operates as set up in 1912 and the climatological returns make a useful contribution to the data received from the Network.

Agricultural interest in climatology had also been apparent from the early days (for example Rothamsted), but it was not until 1924 that the Office took steps to organize this for the benefit of the Network. The interest in observing at agricultural colleges and research institutions arose from the need to monitor environmental conditions in connection with experimental work in crop management and animal husbandry; there were clear advantages for them in achieving uniform standards throughout the country, and these could most readily be obtained through the regular Meteorological Office inspections which were offered in exchange for routine climatological returns. A new class of Crop Weather (now called Agro-meteorological) stations was therefore introduced, and these have become a significant part of the Network. Although not included in this category, an important group of stations with somewhat similar interests has also been established by the Forestry Commission, Nature Conservancy and Field Studies Council.

For the first 35 years, the synoptic stations that were also part of the Climatological Network were almost entirely Auxiliary, the Meteorological Office contributing data only from a few Observatories. However, the applications of meteorology to artillery and flying became evident during the First World War, and from 1920, climatological returns were received from the meteorological offices (then called distributive stations) that had been established at Army units and airfields. Many new meteorological offices were needed to support the Royal Air Force during the Second World War and these too made returns. Fortunately the sharp post-war decrease in the number of offices associated with the Royal Air Force has been partly offset by the increase in those serving civil aviation and the general public, and the Office now makes a very substantial contribution to the total amount of data collected from the Network. Whereas the basic information supplied by all Network stations consists of readings made daily at 09 GMT, these alone give little indication of the important diurnal variations of weather; to obtain knowledge of that, hourly or at least 3-hourly observations are needed, and with the exception of a handful of Auxiliary stations, only the continuously manned meteorological offices can supply these.

Table II summarizes the present distribution of stations in the Network; in addition to the groups specifically mentioned above, certain stations run by Government, Water and other Public Authorities have now been enrolled.

THE CO-OPERATING OBSERVERS

Meteorological offices are manned by professional staff whose job it is to make weather observations, and the observers at Auxiliary stations are for the most part on duty for other purposes and also receive honoraria for their climatological work. By contrast, the co-operating observers as a class are sustained largely by their own interest in a task to which they have voluntarily put their hands. Admittedly, observers at stations which are sponsored by an Authority or Institution fit their meteorological work in with their other duties, and in some cases receive modest extra payments; but many of them carry out work far beyond that strictly paid for by their employers. Private observers, moreover, work entirely in their own time and in most cases purchase their own instruments;

TABLE II—CURRENT SPONSORSHIP OF STATIONS IN THE UK CLIMATOLOGICAL NETWORK

Sponsor		Percentage of Network stations
Meteorological Office		11
Auxiliary Station Authorities		9
Co-operating Station Authorities		80
Local Authorities (General)	12 } 19	
Local Authorities (Health Resorts)	7 }	
Agricultural Colleges & Institutes	14	
Universities, Scientific Institutions, Colleges and Schools	13	
Private Individuals and Estates	11	
Forestry Commission, Nature Conservancy & Field Studies Council	8	
Water Authorities	6	
Other Government and Public Authorities	7	
Miscellaneous (including Industry)	2	

their motivation can only be that provided by a deep personal interest and a spirit of service. Their dedication often puts the professional to shame; more than one private observer has offered to move his home to a place where there is a serious gap in the Network.

All good observers take a pride in their work, and there is perhaps a special satisfaction in having recorded an extreme of some sort. Of all the elements observed, it seems to be sunshine which attracts particular devotion, and the hope of recording as much sunshine as possible has led to sunshine recorders being sited in some very inaccessible places on the roofs of buildings. At Penzance for example, access to the recorder involves scrambling through the mechanism of a large public clock, avoiding moving cogwheels, turning rods and suspended weights (interference with which would stop the clock), in order to emerge from the tower on to a roof. There is, however, another reason for the popularity of the inaccessible, namely security, because sunshine spheres are now very expensive items to replace. Some years ago, during the summer seasons, sunshine spheres were lost with monotonous regularity from the enclosure at Rhyl which was located near a large amusement park; most of these found their way into the tents of gypsy fortune tellers from whom they were eventually recovered by the Police. Three examples, all involving sunshine measurement, will serve to illustrate the lengths to which a dedicated observer will go in carrying out his self-imposed duty.

The station at Botwnnog in Gwynedd is located at the local school, and under the direction of Mr R. L. Jones, then Physics master, the enclosure was always impeccable with grass of bowling-green quality. When a sunshine recorder was to be installed, a firm support was needed and it was decided that nothing less than solid rock would be satisfactory; a massive stone about 6 feet high and weighing several tons was dragged on a flat wooden trolley by teams of boys over 3 miles from a local quarry.

The saddest event in the history of the Network occurred at Teignmouth in 1963. The sunshine recorder was sited at the end of the pier which was under repair at the time; a 60 foot length of decking had been removed, and the sole access was by means of a temporary gangway of single width plank with only a hand rope for support. Whilst trying to reach the pier end to change the card during a severe gale, Mr Rossiter the observer slipped or was blown into the sea and drowned.

At Shanklin, the sunshine recorder is located on the roof of the municipal theatre, and access is by means of a 30 foot vertical iron rung ladder to a catwalk above the stage, then via another ladder and a trap door to the roof. The observer Mr Hoare, aged 82 and a sufferer from chronic arthritis, had the misfortune one evening in 1977 to fall whilst on the catwalk and dislocated his shoulder. To descend the long vertical ladder was clearly impossible, but he managed to climb single handed up to the roof where he changed the sun card and eventually managed to attract the attention of a passer-by in the street below. On arrival, the Fire Brigade ladder was found to be too short to reach the roof, so he was finally rescued on a stretcher by Naval helicopter and taken to hospital for attention. After this episode he was persuaded to retire, but sent to the Office a characteristic note complaining that, unnecessarily, 'a youngish man had now been thrown on the scrap heap'.

Recognition of long service as a co-operating observer

The spirit of dedication to which reference has already been made has not surprisingly resulted in many observers continuing to contribute to the Network over very long periods. The record so far is believed to be 68 years of continuous observing. It is fitting that some official mark of recognition and appreciation should be made to those who give outstanding service to the cause of meteorology in this way, and in 1937 financial approval was obtained to make a strictly limited number of presentations of suitably inscribed barographs. Over the 42 years that this scheme has been in operation, 48 presentations have been made. A list of the recipients and their periods of observing is given in Table III. Not surprisingly, many of those honoured in this way have been great characters, and more than one was still observing in his nineties. It is not possible in an article of the present length to describe the activities of all of them, but notes on some are reproduced in an Appendix; it is apparent from these notes that the dedicated observers were men and women of wide interests, and it is more than a little surprising that despite all other activities, their meteorological work continued so regularly for so long.

Acknowledgements

I wish firstly to record the gratitude of the Meteorological Office for the work of all those observers who have contributed to the Network during the 94 years of its existence. Observations are the lifeblood of meteorology, and without this massive and continuing contribution from the Auxiliary and Co-operating Observers, the national climatological archive would be immeasurably poorer. Secondly I must express my grateful thanks to Mr G. M. Roberts who looked after the Network in England and Wales for many years, and to Mr N. F. Hirst who is still very much involved with the Network in Scotland; without their unrivalled knowledge of events and personalities, this article could not have been written.

TABLE III—AWARDS MADE TO CO-OPERATING OBSERVERS

Year of Award	Recipient	Station	Total period of observations	Total years
1937	Mr C. Webster	Gordon Castle	1879–1939	60
1937	Dr T. E. Saxby	Baltasound	1904–1952	48
1937	Mr J. Baxendell	Southport	1887–1938	51
1938	Mr G. Reid	Crieff	1907–1939	32
1938	Mr C. L. Brook	Meltham	1881–1939	58
1938	Mr C. Dales	Bournemouth	1877–1945	68
1939	Mr A. W. Shadick	Clacton-on-Sea	1901–1939	38
1939	Dr C. C. Vigurs	Newquay	1903–1936	33
1940	Mr J. Dover	Totland Bay	1887–1948	61
1940	Mr M. T. Foster	Cullompton	1911–1947	36
1940	Mr A. Lander	Canterbury	1900–1945	45
1951	Mr J. H. Willis	Norwich	1911–1948	37
1951	Miss N. G. Abercrombie	Ventnor	1923–1951	28
1951	Mr J. Ward	Welshpool	1920–1950	30
1951	Mr C. J. Liness	Buddon Ness	1909–1973	64
1951	Mr I. H. Gordon	Banff	1923–1958	35
1954	Mr K. Durston	Bude	1913–1956	43
1954	Mr J. R. Lloyd	Shinfield	1917–1963	46
1954	Mr J. G. Balk	Oxford (Radcliffe)	1903–1954	51
1954	Mr A. H. Hookham	Eastbourne	1919–1957	38
1954	Mr D. H. Owen	Birmingham (Sparkhill)	1905–1955	50
1955	Mr F. A. C. Cullen	Bognor Regis	1923–1954	31
1955	Mr W. C. Game	Rothamsted	1911–1962	51
1955	Mr J. S. Burgess	Reading University	1918–1960	42
1956	Miss M. M. Evans	Lletty-Evan-Hên	1927–1956	29
1956	Mr H. J. Sargent	Bexhill	1924–1972	48
1956	Miss E. W. Pilkington	Buxton	1923–1962	39
1956	Mr T. Wilson	Keswick	1926–1960	34
1956	Mr E. Hendy	Bolton	1907–1957	50
1959	Mr H. Clarke	Clacton-on-Sea	1924–1960	45
1962	Mr J. Sainsbury	Regent's Park	1932–1962	30
1969	Mr Seton Gordon	Duntulm	1933–1973	40
1969	Mr A. M. Campbell	Strathy	1938–1976	38
1969	Mr F. J. Harris	Newquay	1940–1971	31
1969	Rev. Father MacKillop	Fort Augustus	1929–1970	41
1971	Mr W. A. Field	Rhyl	1933–1971	38
1972	Mr W. L. Peck	Eastbourne	1929–1972	43
1973	Dr J. T. Baldwin	Penicuik	1943–	34+
1974	Mr J. C. W. Day	Walsall	1942–	35+
1974	Mr S. J. H. Ridgwell	Maldon	1939–1976	37
1975	Mr P. Potter	Gulval	1935–1975	40
1975	Miss L. Williams	Aber	1942–1975	33
1976	Mr W. Lawrie	Greenock	1941–1975	34
1976	Mr T. C. Smith	Raunds	1942–	35+
1977	Mr H. Hoare	Shanklin	1949–1977	28
1977	Mr L. Atkinson	Scole	1929–	48+
1977	Mr J. Porter	Moneydig	1933–	44+
1978	Sir Adrian Beecham	Shipston-on-Stour	1933–	44+

APPENDIX—NOTES ON SOME LONG-SERVING OBSERVERS

Mr Charles Webster
Gordon Castle 1879–1939

The station at Gordon Castle was set up by the Duke of Richmond and Gordon some time before the Network was established, and observations were first published in the *Monthly Weather Report* in 1909. Mr Charles Webster first acted as deputy to his father who was head gardener, and became Principal Observer in 1891. Like many family gardeners of his era, Mr Webster never officially retired and he carried on observing until his death in 1939 at the age of 81.

Dr T. Edmundston Saxby, OBE
Baltasound 1904–52

Dr Saxby opened the most northerly climatological station in the British Isles on the island of Unst in 1904 and kept the records there until his death in 1952 at the age of 84. Though born in Edinburgh, and a student there and in London, he went to Unst to follow his father as doctor to the island population in 1898. He was a dedicated physician and never took a holiday; indeed in 54 years he only left the island three times, once to attend a sick relative on the mainland and twice to visit Lerwick. In 1911, King Gustav of Sweden awarded him the Order of Vasa (a Swedish Knighthood) for his services to Scandinavian fishermen; the King also offered him the post of physician to the Swedish Court, but he refused to leave the island. In the late 1940s he was awarded the OBE for his services to the community.

On his arrival in 1898, Dr Saxby made his rounds on horseback, but he later introduced the first motorcar to Unst; however, he normally walked to the enclosure each morning, and it was calculated that during the 48 years he covered well over 4000 miles on foot whilst making his observations. During his early years as observer, he built a run-of-the-wind anemometer using a cyclometer, but this was completely wrecked in a severe south-easterly gale; on another occasion he recorded a wind of force 12, and had to cling to posts to prevent himself from being blown over whilst making his observations. His practice included attending to many patients from visiting fishing boats and he often found great difficulty in finding the time to continue observing; he also built clocks as a hobby, but like so many really busy men he somehow fitted in everything and his observational record never faltered. He was a much-loved and well-respected figure on the island, and on the day of his funeral all work on Unst ceased as a mark of respect.

Mr Joseph Baxendell
Southport 1887–1938

The observatory at Southport was endowed in 1871 by a retired cotton spinner, Mr John Fernley, J.P., and the first Superintendent was Mr J. Baxendell Senior, who prior to that time had held a post as 'Time-determining Astronomer and Waterworks Meteorologist', and was later elected FRS. On the death of his father in 1887, Mr J. Baxendell Junior was appointed as Superintendent and Borough Meteorologist of Southport at the very early age of 18; he held this post for nearly 50 years until his retirement in 1936, was actively connected with the station for a further two years and died in 1940, aged 70.

Throughout his life, Mr Baxendell had to contend with persistent ill health; for periods of weeks and even months he was confined to his room, yet he not only gave a thorough training to his assistants but exercised a detailed and conscientious scrutiny of their work so that the observing routine never suffered. He was particularly interested in periodicities, and also carried out statistical work on land- and sea-breezes and the association of rainfall with wind direction, contributing papers not only to the annual reports of his observatory but to the *Quarterly Journal of the Royal Meteorological Society*. It is, however, as an instrument designer that he is best remembered, his major achievements being the Baxendell Anemoscope and the Fernley recording rain-gauge. The former, which records wind directions in great detail on a separate chart, was used in the classic investigation of wind structure carried out at Cardington in the early 1930s, the results being published as a *Geophysical Memoir;* he also designed a combined head to actuate both a Dines velocity recorder and a direction recorder through a single mast.

Mr Charles Dales
Bournemouth 1877–1945

Mr Dales first became interested in the weather in the 1860s when he was a boy of 14, and started making regular observations in 1877; when Bournemouth decided in 1901 to contribute to the Network, he was appointed as Borough Meteorologist, a post he held until his retirement in 1938 at the age of 87. The enclosure was located in his front garden and the sunshine recorder on the roof of his house, to which he climbed daily until his retirement; but even after this, having handed over to his son-in-law as official observer, he continued to take an active interest until his death in 1945 at the age of 93. He attributed his robust health in old age to the facts that he went out in all weathers, often on his bicycle, and was a total abstainer and non-smoker all his life. Like most people appointed as Borough Meteorologist he received plenty of personal and written enquiries from the local community, and his very long period of observing enabled him to take a broad view; thus he considered the occasional extreme events as no more than fluctuations to be expected, and firmly believed that there was no real evidence of climatic change since the mid-19th century.

Dr C. C. Vigurs
Newquay 1903–36
Dr Vigurs was responsible for the climatological station at Newquay from 1903 until his death in 1940 at the age of 72, but he ceased making observations in 1936. In his early days he was a motoring pioneer, owning the first car in Newquay—a de Dion. He was a man of very wide interests, being the author of several books on botany for which he acquired a national reputation, an expert genealogist, and an acknowledged authority on heraldry, folklore and legends. Despite all this and his medical practice, he also found time to contribute frequently to the *Meteorological Magazine.* He was a very unconventional and pithy writer and some of his letters to Headquarters, still preserved on the historical files, make very refreshing reading; they must have created a minor sensation at the time.

Mr C. T. Liness
Buddon Ness 1909–73
Mr Liness first started observing at Tayport in 1909 whilst he was an assistant light-keeper; he became official observer in 1913 and remained there (apart from war service) until 1927. He then moved to Buddon Ness, and although he officially retired in 1950 he was then employed for some years as a caretaker and continued observing until 1973 when he was well into his 90s. He appears to have been an exceptionally fit and active man, and at the age of 93 he appealed to his former employers for a job to keep him occupied. One of his hobbies was growing carrots. He dug a trench in the sand near the lighthouse, filled the bottom with seaweed gathered from the beach and planted his seed in open-ended tubes; the result was carrots about 18 inches long, smelling of iodine.

Mr D. H. Owen
Birmingham (Sparkhill) 1905–55
Mr Owen kept notes of local weather from 1892, but became an official observer for the British Rainfall Organization in 1905 and a full climatological observer in 1907, continuing until his death in 1955 at the age of 84. He was a keen mountaineer, and made a record ascent of Snowdon in the early 1900s. In 1905 he took part in a European contest in predicting weather trends and won his way through to the final; unfortunately this was held in Paris and he was unable to take part because of lack of funds.

Miss E. W. Pilkington
Buxton 1923–62
Miss Pilkington was appointed Borough Meteorologist of Buxton in 1923, succeeding her father who had held the post since 1899; the family connection thus lasted for over 60 years. She also took over the family pharmacy business on the death of her father, and throughout her period as Borough Meteorologist she produced a daily 24-hour forecast entitled 'Buxton Weather Prospects' written in a very bright and breezy style. After her retirement in 1962 she was appointed Curator of the Bexhill Museum.

Mr T. Wilson
Keswick 1926–60
Mr Wilson took over the climatological station at Keswick in 1926 and acted as observer until his death in 1960 at the age of 73; unfortunately the station did not long survive him. He kept a café and guest house in the town, but was also a music lover, historian and naturalist, and was a bell ringer at the local Church for over 50 years. He sang in the Church choir, founded the Keswick Male Voice Choir and was producer for the Keswick Operatic Society. He took a great interest in local history, was well known as a lecturer on Lakeland customs, folklore and dialect, and published several books on these subjects. He was a keen birdwatcher, and his summaries of local weather always included notes on ornithological events.

Mr Seton Gordon, CBE
Duntulm 1933–73
Mr Seton Gordon, the well-known Scottish naturalist and author, set up a climatological station at Duntulm on Skye in 1933. After graduating with an honours degree from Oxford and spending the First World War in the RNVR, Mr Gordon occupied many years wandering all over Scotland studying the people, animals and birds of the Highlands and Islands and gathering material for his books; during that time he lived in crofts, camped on islands

and was once marooned for nearly a fortnight on an uninhabited, unnamed island off the west coast of Scotland. In 1933 he decided to settle on Skye; there with the aid of his first wife who died in 1959 and that of his friend Mr Nicholson (only a few years younger than Mr Gordon, but invariably referred to as 'young Angus') he maintained a series of observations lasting for 40 years. His interest in meteorology stemmed from his student days and never flagged. In addition to his monthly returns, notes on the weather were sent in frequently, not only relating to Skye but to whatever part of the country he had visited that month; there are reports of snow on Ben Nevis in July, snow beds in the Cairngorms, thunderstorms off Skye and so on. Many of these notes are written on small scraps of paper sometimes no bigger than a postage stamp. Like many of his generation he was resistant to change, and when the Meteorological Office introduced a new form for returns, he stuck to the old one; he regarded metric units as the product of foreigners and declined to use them.

Mr A. M. Campbell, BEM
Strathy 1938–76
Mr Alex Campbell was a gamekeeper with the Department of Agriculture and Fisheries for Scotland for 48 years. He first started observing at Strathy in 1938 and apart from a break for war service with the Royal Air Force he kept the record at Strathy for 38 years almost single-handed; indeed for many years he never even took a holiday. Observing at Strathy is not easy, particularly during the winter months; on one occasion Mr Campbell reported drifts over 30 feet deep within a few hundred yards of the rain-gauge. In 1959, he agreed also to read a monthly gauge at Loch Strathy, some 9 miles from his home; the only access was over a rough track and there were times when his car was stuck in the mud or in deep snow-drifts; at other times he made the journey by tractor and although he always tried to get to the gauge on the 1st of each month, he was often forced to abandon his attempts. Since his retirement, Mr Campbell has been employed as a part time gamekeeper, sometimes working up to 14 hours a day during the shooting season; he is still a fit man at the age of 72, and was awarded the BEM in 1977.

Revd Father F. A. MacKillop
Fort Augustus 1929–70
Father MacKillop's interest in meteorology started in his student days whilst he was taking his M.A. in Geography. As a teaching order, the Benedictine Monks run a boys' school at the Abbey, and it was the practice in the 1920s to appoint the newest arrival on the staff as the meteorological observer. Father MacKillop was thus detailed in 1929, originally as a deputy observer; but from 1937 he became fully responsible and the unsatisfactory system of annual changes of observer ceased. Despite becoming Procurator of the Abbey and acting as village priest, Father MacKillop retained a keen interest in his meteorological work until his retirement in 1970.

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A SEPTEMBER MONSOON DEPRESSION AT MASIRAH, OMAN

By K. GRANT
(Meteorological Office, Bracknell)

SUMMARY

Details are given of the later stages of an Indian monsoon depression which travelled unusually far westwards into Arabia in September 1976.

INTRODUCTION

During the last week of August 1976 a vigorous monsoon depression crossed central India from east to west. Most of these depressions slow down and dissipate over northern India, but a few continue into the northern Arabian Sea, sometimes evolving into a mid-tropospheric depression before dying out as a surface circulation (Ramage, 1971; Rao, 1976). This one, however, maintained both a surface and mid-tropospheric circulation for over a week at the beginning of September 1976. Between the 5th and the 7th it was classified by Indian analysts as a cyclonic storm (mean winds 34–63 kn). Disturbances of this nature are known to affect Oman very occasionally in July and August (Pedgley, 1969 and 1970), but are extremely rare in September, which is the driest month of the year at Masirah. The only measurable September rainfall at this station in the period 1943–75 was 0·01 inch (0·3 mm) in 1955. However, on 8 September 1976 the centre of the decaying monsoon depression passed almost directly over Masirah, and 4·2 mm of rain fell. The following account attempts to trace and comment on the observable features of this depression.

DATA USED

NOAA 4 and NOAA 5 unrectified satellite pictures received by Automatic Picture Tansmission (APT) were available, taken in both visible light and infra-red in the morning (about 05 GMT) and infra-red in the evening (about 16 GMT). Masirah surface charts, with all data to the east derived from the New Delhi radio-teletype broadcast, which could only be received for about two-thirds of the 24 hours, were also used; the amount of data from Pakistan was negligible, and very few ship reports were received. Only when the storm was near the coast of India were the surface charts of any use in placing it. For Masirah itself, hourly surface reports, 12 hourly upper winds by radar and 12 GMT radiosonde ascents were available. The anemogram and barogram were also used. Intermittent surface analyses from New Delhi and satellite tropical disturbance summaries from Washington helped to track the disturbance; the analyses were later checked using the *Indian Daily Weather Report*.

TRACK OF DEPRESSION

It was difficult though not impossible to track the monsoon depression using satellite pictures because the major cloudiness was associated with a low or trough at 700–500 mb which was to a considerable extent divorced from the near-surface circulation. In this respect, the monsoon depression is akin to the extratropical depression rather than to the tropical cyclone. In the northern Arabian Sea in summer, circulation is most vigorous at 600 to 500 mb (Miller and Keshavamurthy, 1968). It was therefore decided to track separately the surface centre and the centre of the densest cloud mass on the satellite pictures which would most likely correspond to a maximum of medium-level vorticity.

Figure 1 shows the results of such tracking, using all available data. (The tracks have been smoothed subjectively, account being taken of the variation in reliability of the fixes.) The surface cyclonic storm centre moved out from India on 31 August. After 1 September it curved to the left, slowed down and weakened to become a depression. On the 5th it developed into a cyclonic storm again, increased in speed and moved north then north-west, skirting the coasts first of India and then of Pakistan. On the 7th it was apparently moving quite quickly (12 kn) south-westwards towards Masirah.

From the 1st to the 6th the centre of the medium-to-high cloud mass as shown on satellite pictures also appeared to move in a counter-clockwise loop, but at a considerable distance ($\approx$500 km) to the south-west of the surface centre. These relative positions of mid-tropospheric low and monsoon depression have also been noted by Miller and Keshavamurthy (1968). On the 7th the surface and upper circulations appeared to merge as the storm moved quickly south-westwards. There is some doubt here whether the upper cloud mass was associated

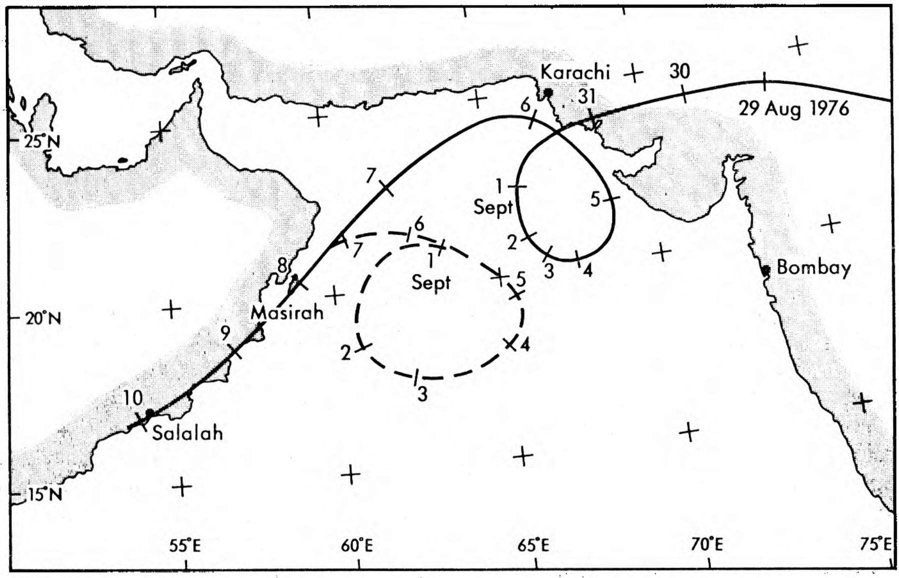

FIGURE 1—TRACKS OF MONSOON DEPRESSION (FULL LINE) AND CLOUDINESS CENTRE (DASHED LINE)

with the original positive vorticity centre, or whether a new vorticity centre was brought from the north-east by the storm. From the 7th onwards no surface centre could be seen on satellite pictures, but the upper cloud showed a more definite elliptical shape, suggesting a better-defined circulation beneath.

PASSAGE ACROSS MASIRAH

The monsoon depression crossed Masirah at about 06 GMT on the 8th, travelling south-westwards at about 7 kn (3½ m/s). It was difficult to decide from surface wind changes on which side it passed, but the main centre must have been within tens of kilometres. The barogram showed a drop of pressure of about 4 mb below previous and subsequent values, the minimum sea-level pressure being 1001 mb (the average 06 GMT value for the time of year is 1007 mb). A fairly steep fall occurred around 05 GMT and an equally steep rise at around 0630. Assuming that the 'eye' of the storm went directly overhead (which is not certain), this gives an eye diameter of about 20 km; no eye was visible on satellite pictures.

Surface winds were variable both before and after passage. During the hours 00–06 GMT on the 8th there were three surges of SW–SSW winds (the normal monsoon direction at Masirah); mean speeds rose to 22 kn at 0040, 20 kn at 0230, then 25–28 kn between 0445 and 0605, with the maximum gust 210° 43 kn at 0520 GMT. Between 0605 and 0630 the wind speed dropped steadily to zero, with a general backing to 060° (though oscillations of gradually diminishing amplitude with a period of 15 minutes in this lighter easterly flow caused a complete 360° veer of wind within a few minutes at 0625). Between 0830 and 1130 GMT light winds veered slowly from ENE to WSW; there was then a further surge of SW winds, mean 21 kn, from 1245 to 1330, then very light north-easterlies. It is not known whether these surges are related to mesoscale features of the depression. They probably correspond to variations in the depth of the SW monsoon flow, which extended up to 100–200 m on this particular day.

There was light rain from about 00 to 10 GMT, though very light and intermittent after passage of the centre. The rain was moderate from 0310 to 0402 and from 0420 to about 0530, these periods coinciding with the slow increase of speed in the last surge of surface wind before the centre crossed. There was a complete cover of altostratus at an estimated height of 3000 m, with little cloud below. An interesting feature was a line of very low stratus of lenticular form at about 100 m which crossed the station from 030° at 0625 GMT, the time of the wind change.

Temperatures in the centre were 25 °C, dew-point 22 °C. In the following easterlies dry-bulb values fell to 23·4 °C. The day maximum temperature was 25·5 °C, below the previous low record for September of 26·8 °C. Table I shows the upper winds at Masirah at 00 and 12 GMT on the 8th, and upper temperatures and dew-points at 12 GMT on the 8th. There was an inversion of 4 K between 987 and 899 mb. The most noticeable feature is the veer of mid-tropospheric winds from N to NE.

TABLE I—UPPER WINDS AND TEMPERATURES AT MASIRAH ON 8 SEPTEMBER 1976

Time	Winds (°/kn) 00 GMT	Winds (°/kn) 12 GMT	Temperature 12 GMT *°C*	Dew-point 12 GMT *°C*
Pressure or height				
100 mb	075/39	075/33	—76·5	—
150 mb	075/30	075/28	—68·7	—
200 mb	095/24	055/17	—50·3	—
250 mb	070/21	030/21	—36·5	—45·5
300 mb	045/16	020/24	—27·1	—35·1
400 mb	350/04	010/10	—14·1	—22·1
500 mb	350/21	035/21	—5·1	—10·8
4500 m	355/37	—		
600 mb	—	045/36		
3600 m	345/25	—		
700 mb	340/21	355/29	+8·2	+4·6
2100 m	016/16	—		
800 mb	—	320/23		
850 mb	030/15	325/17	+22·6	+9·6
900 m	050/09	285/04		
600 m*	070/07	098/04		
300 m	175/08	—		
200 m*	195/16	231/05		
Surface (1001 mb at 12 GMT)	210/13	280/15	+24·6	+22·8

* These values were not included in the transmitted message but have been estimated additionally.

CONCLUSIONS

The monsoon depression which crossed India at the end of August 1976 executed a counter-clockwise loop in the northern Arabian Sea, partly as a cyclonic storm, before continuing on a south-westward track along the coast of Oman between the 7th and 10th of September. At Masirah, which received only 4 mm of rain, even though directly in the path of the depression, moderate rain was experienced only for about three hours, that is to say, for a distance of about 50 km ahead of the centre, even though the overcast was pehaps 500 km in diameter. This fact, and the lack of gale-force winds at Masirah, suggest that the cyclonic storm had lost its intensity, presumably because of the fall of sea temperature to about 25 °C near Masirah, and the entrainment of dry air near 850 mb. The steering of the storm by winds at any particular level was difficult to determine; at high levels, a trough in the easterlies passed through Masirah late on the 8th at 300 mb and on the 10th at 100 mb, winds veering from ENE to SE.

REFERENCES

MILLER, F. R. and KESHAVAMURTHY, R. N. 1968 Structure of an Arabian Sea summer monsoon system. *Int Indian Ocean Expedition Met Monogr* 1.

PEDGLEY, D. E. 1969 Cyclones along the Arabian Coast. *Weather*, **24**, pp. 456–468.

1970 Boston, Mass., American Meteorological Society and Geneva, World Meteorological Organization, *Proc Symp Trop Met, June 1970, Honolulu, Hawaii*, pp. EVI 1–6.

RAMAGE, C. S. 1971 Monsoon meteorology. International Geophysics Series, Vol. 15, Academic Press, New York and London.

RAO, Y. P. 1976 Southwest monsoon. Poona, India Met Dept, *Met Monogr Synopt Met*, No. 1/1976 Chapter 7.

NOTES AND NEWS

Meteorological Office Rainfall and Evaporation Calculation System (MORECS)

The first issue of this new weekly service was made available on 5 April 1978. The information is intended for distribution by post and though primarily for use in water management and agriculture it certainly finds application in other, commercial, activities, mostly in the construction industry.

On offer are standard selections of data which experience suggests meet the needs of particular groups of customers, but the service is flexible, in that individual subscribers, if they so wish, may make a personal and more appropriate choice of data from the wide range of information available.

MORECS is an improved version of the Soil Moisture Deficit Bulletin that has been made available by the Meteorological Office for some years past. The new bulletin will be issued at more frequent intervals than in the past; certain weather variables, such as sunshine and temperature, of interest in their own right, are now presented directly, since convenient summaries arise incidentally in the steps leading to evapotranspiration estimates the basic calculations for which have also been improved.

The primary data for the calculations are taken from those arriving and handled by the automated telecommunication network of the Meteorological Office. The first step is to calculate daily values of potential transpiration or evaporation (the soil moisture loss, given that the soil water available places no restriction on the rate of loss) for each of 188 40×40 km grid squares into which Great Britain is divided in the calculation procedure. Average values for each grid square are set against interpolated average values of measured rainfall and a day-by-day running balance is obtained. When potential transpiration exceeds current rainfall, soil moisture reserves are depleted by transpiring vegetation and the accumulated depletion is known as the soil moisture deficit. The program of calculations takes account of the different water-holding capacities of different soils, the different depths of soil explored by the roots of different crops, and the differing rates of water extraction by different crops when soil moisture reserves have been partially exhausted.

When soil moisture deficits are small, rivers and streams show a rapid response to rainfall because of run-off and surface drainage; underground water-holding strata (aquifers) are also replenished by downward percolation. As well as providing information on rainfall and evaporation, the calculations attempt to partition excess rainfall into surface run-off and percolation components. The information presented is obviously basic to the management of stream-flows, reservoirs and ground water extraction, as well as to the manipulation of soil moisture by irrigation to avoid crop production losses. Since the load-bearing capacity of the soil is dependent on the water in surface layers, the information is also highly relevant to the movement of heavy machinery, agricultural or otherwise.

Memorial plaque: the Akrotiri tragedy

A plaque in memory of Mr J. A. Flawn and other meteorological staff who died as a result of the aircraft accident at RAF Akrotiri on 7 December 1977 was put up on 21 April 1978 in the entrance hall of the Meteorological Office main headquarters building in Bracknell. (See Plate II.)

OBITUARY

We record with regret the death on 1 February 1978 of Mr B. J. Moffitt, Senior Scientific Officer, who was on secondment to the Malawian Meteorological Service.

Mr Moffitt joined the Office for the first time in 1947 as a Scientific Assistant. In 1951 he became a forecaster (Assistant Experimental Officer) and during the next 15 years served in a wide variety of forecasting posts at home and overseas, including many UK outstations, London/Heathrow Airport, and Cyprus. In 1966 he was posted to the Synoptic Climatology Branch (Met 0 13) and while there decided to undertake further study. He obtained special leave to read for a B.Sc. in Geography at the University College of Swansea, and took his degree in 1973. He was promoted Senior Scientific Officer in 1974. In February 1976 he was seconded to Malawi to become chief of the Climatology Branch of the Meteorological Service.

It is with regret that we record the death on 22 February 1978 of Mr C. A. Robinson, Scientific Officer, of the High Atmosphere Branch (Met 0 19).

Mr Robinson joined the Office as a Scientific Assistant in 1947 and served for several years at Shawbury. After a long period overseas in the Middle East, where he was promoted Senior Scientific Assistant, he was posted to Bracknell in 1961 and served in several Headquarters Branches including Telecommunications, Operational Instrumentation and Rainfall.

In his early years in the Office he played Rugby football and later on took a great interest in railways. He was much liked by all who came in contact with him.

We record with regret the death on 14 March 1978 of Mr H. Heastie, formerly a Principal Scientific Officer at the Meteorological Office College, little more than a year after his final retirement from his post as a re-employed Senior Scientific Officer. He had become known to very many meteorologists, British and foreign, through his work at the College, where his lectures were noted for clarity of exposition and emphasis on the physical realities underlying mathematical symbolism.

Harry Heastie graduated with first-class honours in mathematics at London University in 1935 and obtained an M.Sc. in hydrodynamics and algebraic geometry in 1937. After joining the Office in 1940, he served as a forecaster in the United Kingdom and Iceland, and after the war continued to work as a practical forecaster until 1954, chiefly at London/Heathrow Airport. He then joined the Upper Air Climatology branch at Harrow, where his work led to the publication of *Geophysical Memoir* No. 103 'Upper Winds over the World'. After a couple of years in charge of Lerwick Observatory he joined the College (then known as the Training School) in 1960. He retired from his established position in 1975, but was re-employed in order to prepare the second edition of 'A Course in Elementary Meteorology'.

A man of wide general knowledge of literature and the arts as well as meteorology, Harry Heastie was regarded with affection by all his colleagues. He was always ready to take time and trouble to help individual students with their difficulties, often by showing them how a problem could be looked at in several ways, at least one of which would yield the desired illumination.

THE METEOROLOGICAL MAGAZINE

NO. 1272 JULY 1978 VOL. 107

CONTENTS

NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, and marked 'For Meteorological Magazine'.

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Complete volumes of 'Meteorological Magazine' beginning with Volume 54 are now available in microfilm form from University Microfilms International, 18 Bedford Row, London WC1R 4EJ, England.

Full size reprints of out-of-print issues are obtainable from Johnson Reprint Co. Ltd, 24–28 Oval Road, London NW1 7DX, England.

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1 monthly **Annual subscription £13.14 including postage**

Dd. 595890 K15 6/78

ISBN 0 11 724801 0
ISSN 0026–1149

Met.O.915
METEOROLOGICAL OFFICE

the meteorological magazine

AUGUST 1978 No 1273 Vol 107
Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.915

THE METEOROLOGICAL MAGAZINE

No. 1273, August 1978, Vol. 107

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FGGE—THE GLOBAL WEATHER EXPERIMENT

FGGE is the acronym for First GARP (Global Atmospheric Research Program) Global Experiment. The following account is a slightly shortened version of a WMO Press release. We hope to publish an article before the end of 1978 describing the contribution of the Meteorological Office to FGGE.

The World Meteorological Organization (WMO) has launched one of the largest and most complex scientific undertakings ever attempted. Thousands of scientists from virtually every country in the world will be using the most sophisticated tools such as earth satellites, instrumented aircraft, ships, balloons, free-floating ocean buoys, and gigantic high-speed computers to subject the entire atmosphere of the earth and the sea surface to the most intensive surveillance and study ever made. The experiment will last for one full year with two separate periods of two months for special observations in the tropics and southern hemisphere. The purpose of this highly co-ordinated international effort is to ascertain the attainable limits of weather forecasting and to investigate the mechanisms underlying climatic change. The extension of the range of accurate weather forecasts and better understanding of climate variations both have enormous economic value.

Meteorology—both public service and science

The research side of meteorology has so far not caught the public eye. Governments and the citizens at large have tended to see meteorology exclusively as a public service. There is, however, an increasing recognition that the science of meteorology must develop further to meet the ever-increasing national needs for extended weather forecasts and warnings to protect life and property and to meet the many daily requirements for weather information. On the international level this recognition was evidenced by United Nations General Assembly resolutions adopted as far back as 1961 and 1962. These resolutions are the immediate origin of the World Meteorological Organization's major operational activity, the World Weather Watch, and the important research activity, the Global Atmospheric Research Program (GARP). The success of both of these programs has made possible the Global Weather Experiment.

The fundamental problem of meteorology

What then is this gigantic research project involving so many thousands of scientists and their ingenious technological equipment? In order to find out how far ahead the weather can be forecast, meteorologists must obtain a better understanding of the behaviour of the global atmosphere and the physical processes underlying that behaviour. This will enable them to develop improved mathematical–physical models of the atmosphere which will be used in the effort to make weather forecasts more reliable and of longer validity. Successful accomplishment of these two formidable tasks will also make it possible to work towards designing a cost-effective global observing and forecasting system for routine use by the nations of the world, that is to say, an even more effective World Weather Watch.

The nub of the problem—and it has not changed significantly in the more than one hundred years of the existence of WMO and its predecessor organization IMO—is how to improve weather forecasts. The fundamental problem of accurately forecasting the weather presents two basic difficulties. The first is to obtain rapidly enormous quantities of precisely observed data covering such elements as atmospheric pressure, temperature, humidity, and wind speed and direction at the earth's surface and at different heights from an adequate global network of observing platforms using different techniques. At the present time there is still a lack of weather observing stations, especially over the oceans and in the southern hemisphere. The second difficulty is to process these enormous quantities of data equally rapidly (otherwise the weather forecast might well be out of date before it appeared).

Until recent times practical day-to-day forecasting was done mainly by plotting the weather observations on maps and analysing the major weather systems, that is to say, areas of low pressure and high pressure. Partly on the basis of theoretical considerations, but also and very largely on the basis of his own experience, the forecaster would determine the future speed and direction of these systems and the extent to which they would intensify or diminish. This would lead him in turn to a forecast of the weather which would be associated with the systems.

The mathematical revolution in meteorology

About 60 years ago a British meteorologist, L. F. Richardson, devised a procedure whereby the weather could be predicted by mathematical equations based on well-known physical laws. At the time his procedure smacked of science fiction. It would have required 64 000 mathematicians working with calculating machines day and night throughout the year, processing surface and upper-air data received from 2000 weather stations scattered over the globe. But Richardson was no idle dreamer. He originated what we now call numerical weather prediction. This technique became practicable 25 years later. The American mathematician John von Neumann was the first to use an electronic computer operated by a team of meteorologists and mathematicians to analyse and predict weather by mathematics and machines.

The technological revolution: satellites and computers

The technological revolution which produced high-speed electronic computers also produced artificial earth satellites in the 1950s which opened a new dimension in weather observational capacity. Today in the words of a great Norwegian meteorologist, the late Sverre Petterssen, 'the principal technological barriers have yielded. . . . . It has now become possible to keep the whole atmosphere under constant surveillance and to process vast volumes of data on a "real-time" (instantaneous) basis'. Without this technological revolution we should not have today's global weather observation scheme known as the World Weather Watch. Nor would it be possible to launch the present Global Weather Experiment.

A major problem facing research meteorologists trying to improve atmospheric prediction models—and hence to obtain better forecasts—is that they do not have a really satisfactory world-wide set of observations with which to test their models. Scientists specify that an ideal data network would be observation stations spaced 500 km apart collecting pressure, temperature, humidity and wind data at different heights up to 30 km. Without such a data set it is not easy to distinguish between those forecast errors which are due to inadequacies of the models and those caused by the lack of good observations. A good global data set for the whole year and thus covering all the seasons would be invaluable. This is the task of the Global Weather Experiment.

The Experiment and the need for more data

One thing is clear. In order to improve atmospheric models, the Global Weather Experiment must collect a more complete set of data on the condition of the atmosphere globally than is now available from existing observational stations.

The Build-up Year for the Global Experiment began on 1 December 1977. Some of the scientific tools needed for the Experiment such as satellites and the communications and data-processing system will be brought into operation. The preliminary data-collection period started on 1 January 1978. Observations from World Weather Watch stations and satellites in operation will be collected and analysed to enable the data transmission and processing system to be tested. The Operational Year begins on 1 December 1978 when the basic observing and data processing system goes into full operation. This phase of intense global coverage will last for 12 consecutive months. During that year there will be two special observing periods: 5 January–5 March, and 1 May–30 June 1979.

The basic observation system

The basic observation system during the whole 12 month period of experiment will be WMO's global weather system, the World Weather Watch (WWW). In any 24 hour period WWW collects, and transmits to processing centres, standard meteorological observations from more than 9200 land stations making surface observations, nearly a thousand stations making upper-air observations, 9 fixed ocean weather ships and some 7400 merchant ships making surface observations only, and reconnaissance and commercial aircraft providing more than 3000 reports daily. The Global Experiment will be the first occasion where a truly integrated system of satellites is used to observe the earth's atmosphere. Five geostationary satellites will continuously monitor the equatorial and subtropical belts the world round, and a series of polar-orbiting satellites will be used to determine the temperature structure of the atmosphere as well as to provide information on cloudiness and the temperature of the sea.

Inadequacy of the basic observation system

The enormous masses of observational data collected are nevertheless inadequate for a valid global experiment. The ideal requirements of research meteorologists are for a data set consisting of intensive meteorological observations from the entire globe for a full year. This is impossible for financial reasons alone. As a measure of how expensive this kind of research is, the annual cost of operating one fixed ocean weather ship is about $2 million. An ideal project would call for 200 ships just to cover upper-air observations in the tropics alone. A compromise is necessary between what is scientifically desirable, what is technologically feasible and what is economically attainable.

Additional special observation systems to attain global coverage

The scientists managing the experiment have therefore gone ahead with a less perfect but reasonably satisfactory scheme. They will fill the gaps by means of Special Observing Systems. The observational plan includes two specially chosen periods mentioned above (5 January–5 March, and 1 May–30 June 1979). During each of these periods there will be concentrated observational coverage for 30 days.

The gaps to be filled by data collection during the Special Observation Periods relate largely to upper-air information needed from the equatorial tropics, and surface pressure and temperature from the vast ocean areas of the southern hemisphere. To collect this information a formidable assortment of highly sophisticated scientific and technological tools will be used.

Data collection in the tropics especially over the oceans

First, to obtain upper-air information from the tropics, rawinsonde balloons released from land stations and from some 50 ships will be used. The development of a special rawinsonde system for deployment on ships has been undertaken by WMO.

To supplement these activities over the tropical oceans not adequately covered by ships, instruments called dropwindsondes will be used. These are to be released from about 12 aircraft flying each day at an altitude of about 9–12 km over carefully planned courses in the Indian, eastern and central Pacific, and Atlantic Oceans. As the instruments descend they will transmit back to the aircraft information on pressure, temperature and humidity as well as their true locations which they pick up from an Omega Navigation System. These data are then to be fed into the main data-processing system.

Additional data will be collected by commercial jet aircraft equipped with apparatus which automatically records on magnetic-tape cassettes. These data can have special value when the aircraft is flying over areas from which other reliable observations are sparse. This will increase the information gathering resources by some 80 commercial airline aircraft. A number of other commercial aircraft will install equipment for automatic transmission of meteorological data to ground stations via satellite (ASDAR).

To obtain data above the level at which the aircraft fly, use will be made of a series of about 300 constant-level balloons. These will drift along at an altitude of about 14 km and will provide certain required data. The balloons will be launched from Ascension and Canton Islands. The signals from the balloons and their corresponding locations are picked up by one of the polar-orbiting satellites and then incorporated into the data-processing system.

Drifting buoys in the southern oceans
From the southern oceans, that other great and normally silent area, information will be collected by drifting buoys. Three hundred of these buoys will measure atmospheric pressure near the sea surface and the temperature of the sea water within the upper one or two metres. Some buoys will also measure air and water temperature and wind speed. All these data are to be picked up in the same way as those from the constant-level balloons (namely by polar-orbiting satellite) and then transmitted to the data-processing centres.

Special research satellites
Another supplementary observing facility will be provided by two research satellites. They will provide radiation data making possible estimates of sea-surface temperature, atmospheric temperature profiles and moisture content, and information on the sea-ice coverage. One will also yield data on atmospheric ozone content and distribution, and the other on wind speed and direction at the ocean surface. This is, of course, in addition to the polar-orbiting and geostationary satellites.

Regional experiments in association with the Global Weather Experiment
Several specialized experiments having to do with significant regional phenomena (Asian monsoon, west African monsoon, and the weather of the polar regions) which are important elements of the global atmospheric circulation will be carried out in conjunction with the Global Weather Experiment. These include projects which collect important oceanographic information that will permit more definitive studies of oceanic responses to atmospheric influences and vice versa. The principal regional experiments have their own scientific aims, but will provide detailed data for the Global Experiment and will benefit, in turn, from the improved global data set provided by the Global Experiment, since the regional phenomena are inextricably linked with the global circulation. These have relevance not only for the task of improving weather forecasts and extending their useful range, but also for studying the physical processes in the atmosphere leading to a better understanding of climate.

The Asian Monsoon Experiment (MONEX)
In order to understand the physical phenomena that bring life-giving rains and cause devastating droughts in Asia, research projects are under way to obtain the data required for a better analysis and evaluation as the basis for improved forecasting and other applications to human activities in the region. Because of the natural division of the monsoon into a winter and summer phase, and because of the regional distinctions in the monsoon between the eastern region and western regions of Asia, two separate efforts are required, namely a winter MONEX and a summer MONEX. Both of these are designed to observe and obtain a more comprehensive understanding of the regional and seasonal fluctuations of the Asia monsoon and its effects on the global atmospheric circulation. The experiments will cover the area of the west Arabian Sea, the north of the Bay of Bengal, and the South China Sea.

The West African Monsoon Experiment (WAMEX)
The west African region, like Asia, is subject to wide interannual variations in rainfall, and is subject therefore to prolonged and severe periods of drought.

WAMEX is an experiment mounted by the countries of the region to take advantage of the enhanced global data coverage during the observational phase of the Global Weather Experiment. It will also contribute significantly by providing increased detail in the tropical observing network required by the Global Experiment. Its principal aim, however, is to attempt to clarify the three-dimensional structure of the monsoon and to understand the physical mechanism which generates and maintains the monsoon. Ultimately it is expected that the improved understanding of the phenomenon in its planetary, regional and subregional aspects will provide the basis for improved forecasting and other practical applications to regional planning.

The Polar Experiment (POLEX)

The polar regions, both North and South, are the major heat sinks in the global atmospheric–oceanic system, and as such constitute a significant element that has to be taken into account in the Global Weather Experiment. The Polar Experiment (POLEX) is designed to be carried out during the Global Experiment in order to provide an improved data set in the polar regions, provide calibration and 'ground truth'* for the satellite observations, and to assist in modelling high-latitude processes that are of importance in the global circulation. These data will also be especially important for assessing the role of snow and ice cover in climate dynamics. Much of this work will be carried out as part of ongoing national and international studies in the polar regions, but within the context of the Global Weather Experiment and the World Climate Program of WMO.

The value of the earlier tropical experiment (GATE)

The Global Weather Experiment will benefit considerably from the GARP Atlantic Tropical Experiment (GATE) which made extensive meteorological and oceanographical observations of one-third of the earth's tropical belt from 15 June to 30 September 1974. The purpose of that activity—until the Global Experiment, the largest scientific experiment ever undertaken—was to collect data which would enable meteorologists to have a clearer picture of the behaviour of the tropical weather systems and their ultimate effect on global weather. GATE was an outstanding success and it will contribute greatly to the planning and implementation of the Global Weather Experiment.

The management of the Experiment

The number of scientists managing the vast global weather experiment is surprisingly small. The management consists of a small group of meteorologists, oceanographers and technical specialists who form a centralized FGGE Operations Centre within the Secretariat of WMO in Geneva. Following the practice of the World Weather Watch, each country participating in the Experiment will look after its own contribution to the gigantic experiment. The total of such contributions is enormous. In addition to the normal contribution of the 147 Members of WMO, all of whom participate actively in the World Weather Watch, 75 of these Members plus five intergovernmental organizations are making special or additional contributions to the Global Experiment and the regional projects related to it. These contributions include funds for such things as special instrumentation, 4 polar-orbiting and 5 geostationary satellites, 43

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* e.g. surface pressure to act as a datum for absolute values of geopotential.

research ships, 12 special research aircraft, 300 constant-level balloons, 300 floating buoys, masses of observational and communications equipment, the time of thousands of scientists and the use of the world's largest computers.

A decade of planning

The role of the Operations Centre is to complete the extensive planning in time for the observational year. The initial planning of the Experiment actually started at a meeting of 50 prominent scientists in Stockholm in 1967. Since then, the detailed planning of every aspect of the gigantic experiment has engaged the efforts of hundreds of meteorologists and technologists in many meetings all over the globe.

The monitoring and co-ordination of the Experiment

Once the observational year begins, the Operations Centre will monitor the performance of the observing system as a whole and initiate corrective actions when necessary on the basis of reports on how the various systems are working. It will also co-ordinate activities with the special and regional programs mentioned earlier. The Operations Centre has available at all times the full resources of the WMO Secretariat, and policy guidance from WMO's Intergovernmental Panel and from a small scientific advisory board, both established especially for the Global Experiment. Finally the Operations Centre will arrange for international assessment of the experiment and prepare a report on the conduct of the experiment and on the experience gained.

Data management and processing

The wide range of observing systems already described will produce an enormous amount of data. The management of these data presents a formidable task far beyond the capacity of any single country or organization. These data will in fact be organized and processed into a complete and consistent set for use in the ensuing research work in many countries. The countries and organizations which will play the major role in this important but arduous task are: Australia, Finland, France, Federal Republic of Germany, Japan, The Netherlands, Sweden, United Kingdom, USA, USSR, the European Space Agency and the European Centre for Medium-range Weather Forecasts.

What happens to the fantastic masses of data collected? The global data sets are used in two quite different ways. First, the meteorological centres of the World Weather Watch in all parts of the world will receive a large increase in the amount of information that normally comes into them. They will receive this in real time, that is to say, almost as it happens. This will enable them to improve the quality of their routine operational services and any research and analytical work that they are undertaking.

Research to start during operational year

Of greater significance, a wide variety of research based on the data sets produced by the Experiment will be carried out by national services, academies and universities. The intensive period of research will begin during the operational year. It will continue for several years thereafter. Areas of study will include prediction and predictability experiments, diagnostic studies, sensitivity experiments, and investigations of seasonal variations. Arrangements are being made for international co-ordination of much of the subsequent research and evaluation and for wide dissemination among scientists of the results of the Experiment.

The possible results of the Global Experiment

At this stage it would be foolhardy to venture a guess as to the specific results of such a gigantic scientific undertaking as the Global Weather Experiment. It may well be that by the middle 1980s the consolidated results will make it possible to extend the useful range of weather forecasts to 10 days or more. But at the moment we cannot be sure. However, we can be optimistic that all this effort on the part of thousands of scientists and technologists and the expenditure by most of the governments of the world of considerable resources will lead to a better understanding of atmospheric motion so that meteorologists can develop better models for weather prediction. We can be equally optimistic that the Experiment will result in a substantial strengthening in the operation and effectiveness of the present World Weather Watch. This could have economic benefits far outweighing the cost of the Global Weather Experiment. Finally the data sets and their study and analysis will make possible a clearer understanding of the mechanisms underlying climate variations, a subject of increasing interest and importance for the whole of mankind.

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A TEST OF DATA ACQUISITION AND PROCESSING FOR FGGE

By M. V. JONES and J. BALLENTINE
(Meteorological Office, Bracknell)

SUMMARY

A Data Acquisition and Processing Test was carried out by the UK Area Sub-centre for Surface-based Data in July 1977 in preparation for FGGE. Statistics of the data collection are presented, together with some suggestions for improved data capture in the future.

INTRODUCTION

The First GARP (Global Atmospheric Research Program) Global Experiment (FGGE) is an attempt to improve meteorological telecommunications and computing resources over the whole world and to use them to attack the problem of the medium-to-long-range predictability of the atmosphere. An unprecedented collection of observations is planned, involving both conventional techniques and specially deployed observing equipment. The Operational Year of FGGE will begin on 1 December 1978, and will be preceded by a Build-up Year.

There are detailed plans for assembling these data, involving many collecting centres in nine countries. The Meteorological Office acts as an 'Area Sub-centre', with responsibility for collecting surface, radiosonde and pilot-balloon observations from Europe (WMO Region VI excluding USSR), Africa (including the Atlantic and Indian Ocean islands in WMO Region I), and the Middle East (WMO Block 40, namely Syria, Lebanon, Israel and Jordan in Region VI, and Iraq, Iran and the Arabian peninsula in Region II). Two other categories of observations are to be included in the collection, namely all aircraft and surface ship reports received in real time via telecommunication channels from anywhere in the world. Similar observations from the rest of the world are to be collected by three other Area Sub-centres.

Such data are described as 'surface-based'. The observations are assembled into ten-day periods and sent to the 'Surface-based Data Centre' in Moscow. This centre in turn merges the collections from the four Area Sub-centres and the 'Space-based and Special Observing Systems Data Centre' (in Sweden) for retention at one of the two World Data Centres, also in Moscow. The flow of data is depicted in Figure 1.

THE DATA PROCESSING AND ACQUISITION TEST

As part of these plans the UK Area Sub-centre undertook to execute a test in respect of observations for 1–20 July 1977, that is to say two ten-day periods.

Details are given below, together with some results of the test, and some suggestions for a more effective collecting system. The principal tool available was the 'Synoptic Data Bank' (SDB) which is normally used in real time in support of forecasting and archiving of data.

Data arriving at Bracknell through the Global Telecommunication System (GTS) and domestic channels are checked for correctly formatted bulletin headings, before being submitted to the SDB. The SDB software inspects the bulletin headings in order to sort the observations into types (SYNOP, TEMP,

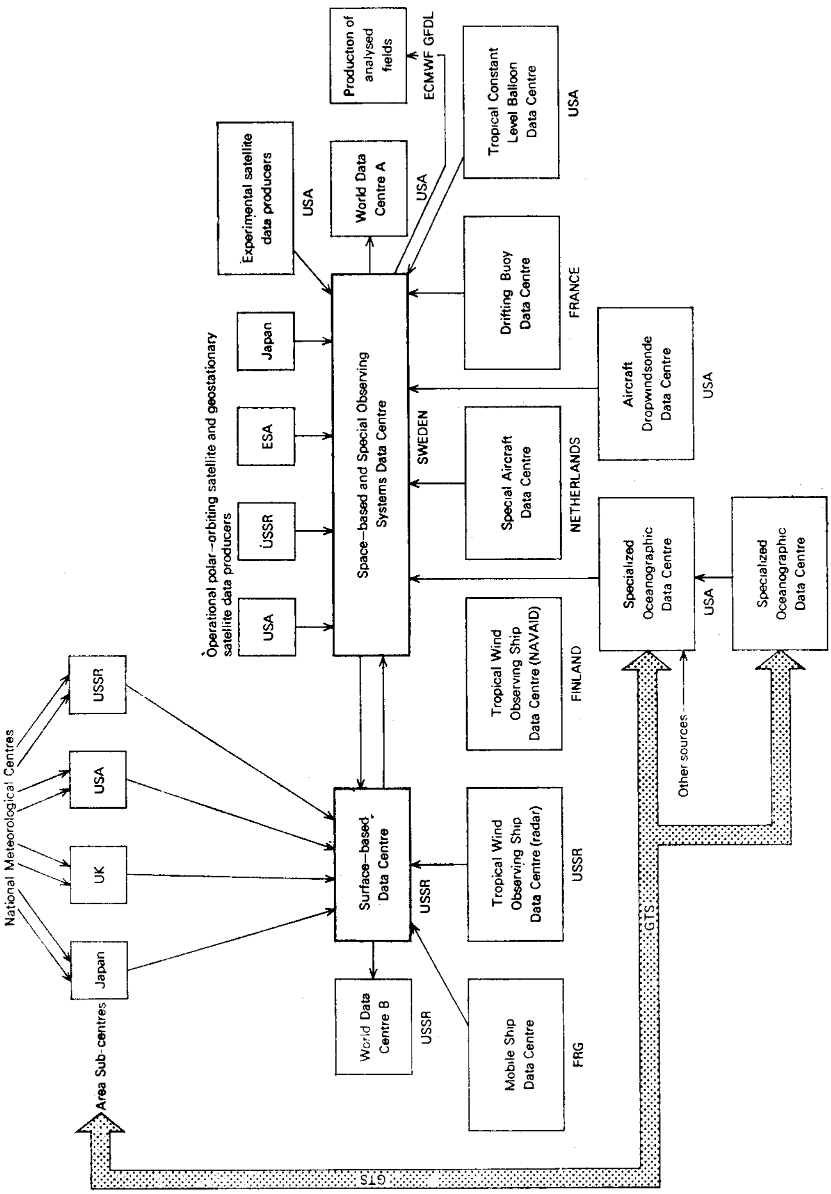

FIGURE 1—THE SCHEME FOR COLLECTION OF DELAYED DATA

ECMWF = European Centre for Medium-range Weather Forecasts
GFDL = Geophysical Fluid Dynamics Laboratory (USA)

AIREP etc.) and, after applying quality-control procedures, stores them in data sets. One data set (a 'bank') contains 12 hours of reports, and in normal operation reports may be stored if they arrive within 36 hours.

Software has been written to inspect the banks, so that their contents may be monitored at any time in terms of observation type and geographical area. An extension of this technique enables a bank to be analysed by time of storage. These two facilities will be referred to below as 'Data Monitoring' and 'Time of Receipt' respectively. After 60 hours of immediate accessibility by computer programs and enquiry terminals each bank is copied to magnetic tape for five years' retention.

Collection from Region VI and ocean weather ships

Bracknell receives almost all the available reports from Europe and Ocean Weather Ships (OWS) and also from Syria, Lebanon, Israel and Jordan, so that the real-time SDB in this case almost meets the requirements of FGGE. However, during this test period the Data Monitoring program was run after 36 hours to identify any missing or corrupt observations, from any of the 32 National Meteorological Centres (NMCs), so that we might request a repeat of those reports from the appropriate NMC. OWS observations were not monitored.

It is interesting to note that most observations identified by the program were missing rather than corrupt. From the correspondence received from the NMCs it appeared that many of the requests referred to observations which were no longer made, that is to say that the station lists used were out of date, even though a great effort had been made to keep up with notified changes.

The NMCs were asked to send their late observations on 5-hole paper tape within 60 days, so that they could be read into the computer alongside the observations from Africa and the Middle East.

Collection from Region I and the Middle East

Experiences gained a few years ago with the GARP Atlantic Tropical Experiment (GATE) indicated that the collection of observations from Africa on 5-hole paper tape (as used in telecommunications) was practicable.

Firstly it was necessary to request (through WMO) the participation of 53 NMCs and ask for a contact in each NMC. On receiving a formal agreement, three fibre boxes and some detailed instructions were to be sent to each NMC. The boxes were to be used to post observations back to the Area Sub-centre, with seven days' data in each box.

Careful instructions were sent with the boxes. Again, experience with GATE was helpful, as was conversation with the occasional African visitor to the Meteorological Office at Bracknell.

Data processing

During the test period itself the only data processing was that involved in the normal operational Synoptic Data Bank activity, together with Data Monitoring of European observations as described above.

The plans allowed a period of 73 days after the last observation for each box to return to the United Kingdom, so that reading paper tapes for 1–7 July was begun on 18 September.

This phase of processing was in three parts: firstly to copy the contents of paper tape into a disc data set, secondly to add those observations to the appropriate bank (previously copied back to disc from an archive magnetic tape), and finally to extract the required observations for arrangement into the format necessary for dispatch on magnetic tape to Moscow.

The first phase took place during the day, when staff were available to operate the paper-tape reader and the visual display unit (VDU) used for control. By means of the VDU it was possible to display the first few characters from each tape, as a check that the tape had been mounted correctly. This facility also proved invaluable for deciding how to process some of the tapes which arrived with formats bearing little resemblance to those we had requested.

The second and third phases took place overnight, since no special operator action was required other than to ensure that the jobs were run in the correct order. During these phases the extra observations were incorporated into our own archives.

Each magnetic tape was dispatched (on time) to the Surface-based Data Centre via the Foreign and Commonwealth Office.

Quantity of data received

Region VI

The exact numbers of observations collected in response to Data Monitoring messages were not measured. However, it is true to say that every European NMC received notification of at least one missing observation during the 20 days. Some of the missing observations were in fact reported as NIL, but could not be recognized as such by the SDB software.

In reply to the messages 192 paper tapes were received. Some of these tapes contained all the observations for the particular day rather than just the missing or corrupt observations that were requested. Such tapes could be used, but some tape-reading time and disc space were unnecessarily occupied. Tapes from two NMCs were received too late to be of use.

These results are summarized in Table I(a).

Africa and the Middle East

Table I(b) presents an analysis of the extent of participation in the collection of delayed data by African and Middle Eastern countries.

The principal question to be asked about the collection of delayed data is: 'How many more data have been collected than were available in real time?'. So as background information, Tables II and III present statistics of the collection of data in real time from Africa and the Middle East.

Table II is extracted from the results of a survey carried out at Bracknell in connection with World Weather Watch (WWW). Observations from Region I (Africa) were monitored in real time from 1 to 15 September 1977 as they arrived in the Synoptic Data Bank. The table shows that in general less than half the expected data are received within six hours.

Table III gives for each time and type of report and each WMO block number the maximum and minimum numbers of reports for any one day (out of the 20 days of the test period) arriving through the GTS within 36 hours. There is an alarmingly large number of zeros in this table, particularly in the upper-air columns. Elsewhere there are indications of a wide variation from day to day, especially in the southern blocks.

TABLE I—PARTICIPATION 1–20 JULY 1977

(a) *Region VI excluding USSR*
All 32 NMCs had at least one missing or corrupt observation.
192 paper tapes were received in time.
Two NMCs sent data too late.

(b) *Africa and the Middle East*

	No. of NMCs	No. of NMCs who had formally agreed to participate
All data received in time to be incorporated	33	15
Some data received in time, some too late	2	2
All data received too late	4	3
No data received	14	2
Totals	53	22

TABLE II—WWW MONITORING OF REGION I FROM 1 TO 15 SEPTEMBER 1977 AT RTH BRACKNELL

Surface	Percentage received*	
Cut-off (hours)	00 GMT	12 GMT
HH + 1	14	16
HH + 3	22	40
HH + 6	29	47
Missing at HH + 6	71	53

Upper Air	Percentage received*	
Cut-off (hours)	00 GMT	12 GMT
HH + 3	19	23
HH + 6	32	38
Missing at HH + 6	68	62

* The number of reports received is expressed as a percentage of the number expected (according to WMO documents).

TABLE III—MAXIMUM AND MINIMUM NUMBER OF REPORTS THROUGH GTS (PER DAY)

	Time of report (GMT)							
	SYNOP				UPPER AIR			
WMO Block Nos.	00	06	12	18	00	06	12	18
40	57	131	95	101	11	13	15	6
	34	82	88	52	6	0	11	0
60	44	57	59	74	7	30	6	36
	36	49	52	36	4	24	3	26
61	44	66	65	56	2	37	9	40
	13	49	39	15	0	12	3	10
62	24	38	40	25	6	23	4	3
	0	13	20	16	1	2	1	0
63	31	59	53	25	4	12	5	0
	12	7	0	0	0	1	0	0
64	19	52	47	54	0	13	3	7
	0	0	0	0	0	0	0	0
65	20	47	39	30	0	7	2	13
	12	17	16	3	0	1	0	0
66	1	14	15	11	0	0	1	0
	0	0	0	0	0	0	0	0
67	24	94	63	41	6	24	3	0
	0	2	0	0	0	0	0	0
68	42	86	89	95	12	2	10	0
	16	24	0	3	0	0	0	0

The postal data were added to the data banks at some time during the last few hours before midnight GMT, so that they could be distinguished by their 'time-of-receipt'. There were a few occasions where real-time data, particularly for 1800 GMT, had also been stored during those hours, so that the delayed data were indistinguishable—such occasions have been ignored in the following statistics. Figure 2 shows a typical analysis by time-of-receipt of one data bank for a particular block, a particular type of data and a particular datum time. The addition of delayed data can be clearly seen at approximately 820 minutes after 0600 GMT (i.e. 1940 GMT), so that the numbers of reports before and after may be measured. Note that the time of day at which the observation is received is stored, but the 'date-of-receipt' is not, and that in this case the 'delayed' observations were stored at 1940 GMT some 70 days after the observation time.

Table IV is a summary of all the suitable time-of-receipt analyses, expressed in terms of the overall percentage increase of data due to delayed collection for the period. The very high percentages of course reflect the small numbers of such observations arriving over telecommunication channels. The sparsity of the upper-air network accentuates the effect on figures of any data losses due to omission of observations or excessive postal delay—hence several zeros in the table.

Nevertheless the increase of 32 per cent for the whole of Africa and the Middle East over the 20 days is encouraging and justifies the continued effort. This figure is expected to be improved in the future (see 'Suggestions for improved Data Capture' starting on page 241); continued co-operation by the participating countries, especially those acting as Regional Telecommunication Hubs (RTHs), will be very much appreciated.

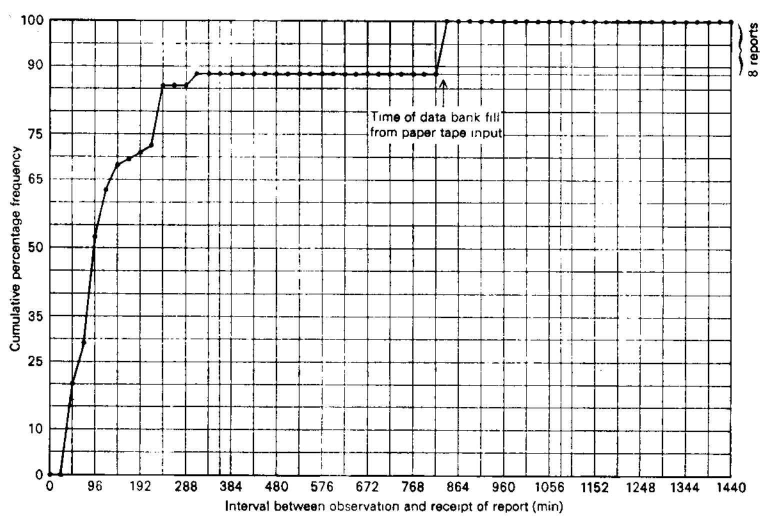

FIGURE 2—TIME OF RECEIPT/FREQUENCY CURVE

Observations at 0600 GMT, 8 July 1977. Surface reports 'SYNOP' for Block 61. Total number of reports = 69. No reports received outside time interval.

TABLE IV—NUMBER OF EXTRA REPORTS RECEIVED BY POST EXPRESSED AS A PERCENTAGE OF THE NUMBER RECEIVED THROUGH THE GLOBAL TELECOMMUNICATION SYSTEM

	Time of report (GMT)								
	SYNOP				UPPER AIR				
WMO Block Nos.	00	06	12	18	00	06	12	18	All times
40	11	4	9	17	7	21	15	10	10
60	7	19	19	23	6	7	0	1	14
61	24	3	8	33	100	8	4	9	14
62	62	62	25	77	10	90	125	60	56
63	25	29	37	68	36	3	105	0	36
64	785	75	90	65	0	85	58	123	98
65	21	8	27	54	0	21	0	27	26
66	700	132	138	224	0	0	0	0	161
67	99	21	50	63	115	148	117	0	50
68	18	8	7	19	0	0	4	0	11
All Blocks	46	22	31	43	22	36	28	22	32

Average percentage increase = 32% for the period.

Table V gives an indication of the variability of numbers of delayed reports from day to day. Again there are many zeros and a wide daily variation.

TABLE V—MAXIMUM AND MINIMUM OF REPORTS ADDED FROM PAPER TAPE (PER DAY)

	Time of report (GMT)							
	SYNOP				UPPER AIR			
WMO Block Nos.	00	06	12	18	00	06	12	18
40	13	7	22	25	2	3	3	1
	0	0	0	4	0	0	0	0
60	4	19	15	17	1	6	0	1
	0	0	0	7	0	0	0	0
61	14	6	9	34	1	4	1	7
	1	0	0	2	0	0	0	0
62	13	31	23	34	1	15	5	3
	0	0	0	2	0	0	2	0
63	8	16	15	24	1	1	4	0
	0	0	0	0	0	0	0	0
64	37	42	58	51	0	8	2	8
	3	9	4	0	0	1	0	0
65	7	8	17	27	0	1	0	4
	0	0	0	0	0	0	0	0
66	1	10	10	11	0	1	0	0
	0	0	0	0	0	0	0	0
67	18	29	45	33	4	16	2	0
	0	0	0	0	0	0	0	0
68	7	8	7	33	0	0	1	0
	1	1	2	0	0	0	0	0

Table VI shows the total numbers of observations of various types and times included on the magnetic tapes sent to the Surface-based Data Centre. There are no great surprises in the table, but it is interesting to note the variation with time of day, particularly with regard to SYNOPs. It should be remembered in this context that the local time corresponding to 0000 GMT ranges between 2300 and 0400.

TABLE VI—TOTAL NUMBER OF OBSERVATIONS SENT TO SURFACE-BASED DATA CENTRE FOR PERIOD 1–20 JULY 1977

Time (GMT)	SYNOP	SHIP	AIREP	UPPER AIR*	TOTAL
00	8 510	11 764	6 438	4 359	31 071
06	13 660	11 014	9 974	3 797	38 445
12	13 320	11 773	7 387	5 633	38 113
18	12 010	11 308	9 250	3 235	35 803
Totals	47 500	45 859	33 049	17 024	143 432
Daily mean	2 375	2 293	1 652	851	7 171

* The upper air reports include all available parts A, B, C and D for PILOT and TEMP reports.

DIFFICULTIES WITH POSTAL COLLECTION

Timing

Some of the boxes intended for return postage of paper tapes were not received by the departments which prepare the data. This was partly because half the containers were posted to addresses supplied from within the Meteorological Office and not to official addresses, since these NMCs had not (at the time of posting) agreed formally to participate in the test.

Even though the containers were posted from the Meteorological Office at Bracknell by air mail on 3 June, some of them did not reach their destination in time. This is probably why 6 sets of data arrived late, and why no data arrived from 14 other NMCs.

Difficulties did occur when data were posted by surface mail from distant countries in the Middle East and South-east Africa as they take 8–12 weeks to arrive at Bracknell.

Content

After the GATE experiment, a report was produced on difficulties found with the collection of data arising from the use of paper tapes. Many of the problems found during GATE recurred with the paper tapes collected during the July test:

Only two-thirds of the tapes had the correct WMO bulletin heading—the other one-third were unacceptable for reading into the computer.

Some tapes were unsuitable for use on optical paper-tape readers, because of incomplete perforation, or because of a non-standard 5-hole configuration on 7-hole width paper.

Some NMCs had compiled several days' observations, not in chronological order, on to one paper tape. These tapes had to be read on a viewer and where possible split into separate days before being used with the other delayed data for the same day. Two NMCs were unable to supply data on paper tape and instead sent them in manuscript form which had to be punched on to 5-hole paper tape at Bracknell.

A few tapes had unwound during transit and were slightly damaged, whilst some were securely held with heavily gummed cellulose tape. Unfortunately the gum from the cellulose tape came off on to the edges of the paper tape and caused sticking on the paper-tape reader head.

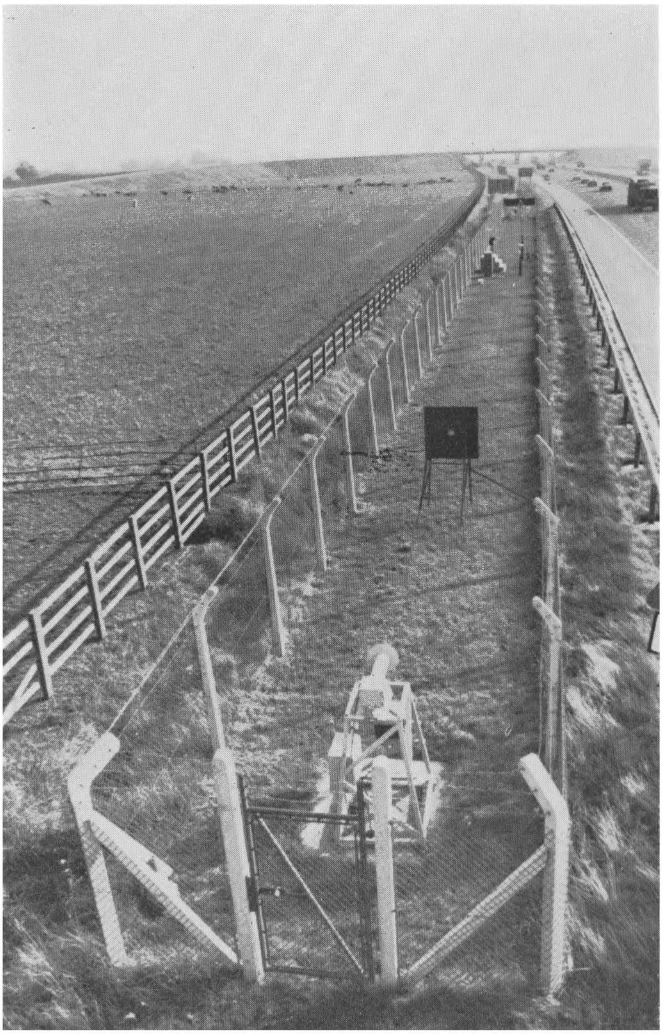

PLATE I—A GENERAL VIEW OF THE CENTRAL COMPOUND LOOKING EASTWARDS

The transmitter unit of the Meteorological Office Transmissometer (MOT) is in the foreground with the other visibility and meteorological instruments midway along the length of the compound. The black screens at the far end and in the foreground were used to prevent drivers being distracted by the light.
(See page 243.)

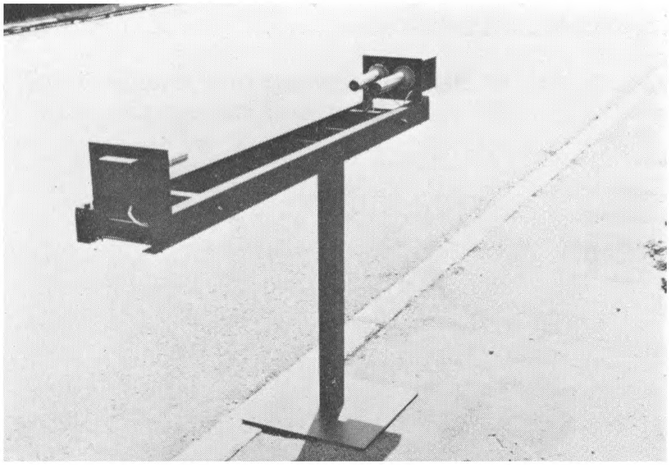

PLATE II—A CLOSE VIEW OF THE INSTRUMENT DESIGNED BY THE TRANSPORT AND ROAD RESEARCH LABORATORY SHOWING THE TWIN TRANSMITTING AND RECEIVING ELEMENTS AT THE FAR END OF THE INSTRUMENT

(See page 244.)

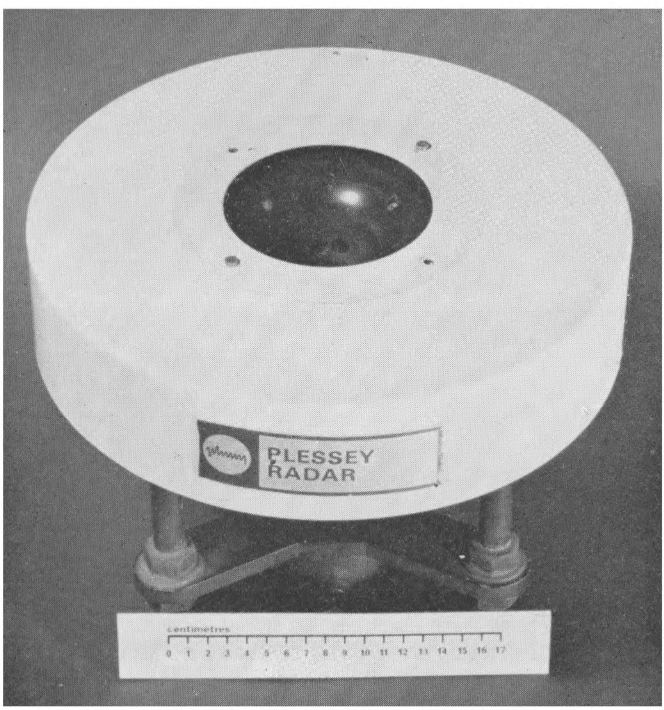

PLATE III—A VIEW OF THE POINT VISIBILITY METER DEVELOPED BY PLESSEY RADAR LTD FOR THE HOME OFFICE

The rule gives an indication of its small size—the unit shown here is mounted on a pole for operational use. (See page 244.)

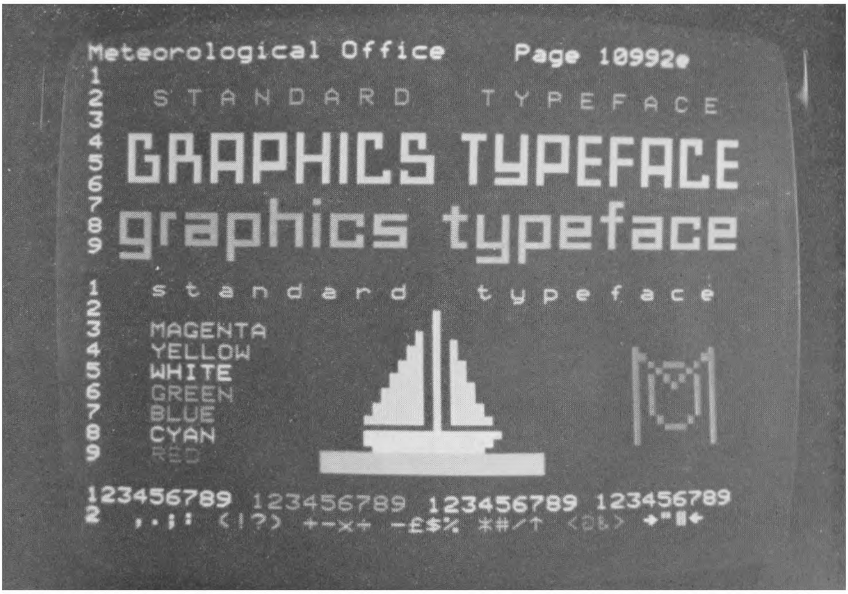

PLATE IV—PRESTEL DISPLAY FORMAT, SHOWING CAPABILITIES OF SYSTEM AND RANGE OF COLOURS AVAILABLE

(See page 252.)

PLATE V—SAMPLE FORECAST FOR A REGION

(See page 253.)

To face page 241

PLATE VI—PRESTEL EDITING TERMINAL SHOWING TELEVISION RECEIVER, EDITING KEYBOARD FOR INPUT AND HAND-HELD KEYPAD FOR SELECTING FRAMES FOR DISPLAY

(See page 250.)

Group collectives

Early in 1976, five RTHs were requested to help during the July trial period by collecting the data for all NMCs in their area of responsibility and sending one tape per day to the Area Sub-centre. Out of the five, four agreed to co-operate, but in the event no collectives were received. Two of them sent their national data, but in both cases they arrived too late to be included.

SUGGESTIONS FOR IMPROVED DATA CAPTURE

Timing

A better list of addresses has been built up with the help of the GARP Activities Office and by direct correspondence with the NMCs. This will help to get the containers to the correct addresses. A supply of six 10-day containers was posted in October to the NMCs who had provided data for the July test. They will receive a steady supply of boxes during the Build-up Year and the Operational Year.

Help has been offered by a commercial company with contacts in the meteorological services of two countries, and this has already proved effective (at the time of writing the Build-up Year has just begun).

Countries which could not meet the 60-day deadline for getting data to Bracknell will be requested to air-mail the data.

Content

To try to reduce the number of observations lost owing to incorrect bulletin headings, a sample paper tape with print-out will be sent to every NMC, showing the layout of bulletin headings and observations requested for input to the computer.

Officers preparing the tapes will be requested not to use adhesive tape but to use special wire-strengthened plastic ties, which will be provided, to hold the data tapes in transit.

A short report on the difficulties found during the July test and suggestions on how they might help to overcome them has been sent to every NMC whether or not they sent data during the tests. Each supply of containers will have precise instructions in English or French for collecting the data.

For the three NMCs that cannot provide paper tapes, data in manuscript form will be punched on to paper tapes. Provision will also be made for a limited number of non-standard paper tapes to be re-cut to 5-hole paper tapes.

Monitoring of missing reports from Region VI will continue. Data sets of station numbers administered by each NMC will be kept up to date to ensure the maximum efficiency of the monitoring program.

Monitoring of the area covered by the postal collection of data will take place after the paper tapes have been added to the GTS data sets, and information about continuing deficiencies in any particular area, such as can be seen from the figures in Tables IV and V, will be forwarded to the GARP Activities Office for possible rectification in the future.

It is unlikely that much manual inspection and correction of meteorological data or bulletin headings will be undertaken as was done for GATE, because this would involve too many staff to keep pace with daily processing of the data. However, it may be possible to amend computer programs to accommodate some of the types of incorrect bulletin headings which were received during the trial period, hence capturing a number of observations which would otherwise have been lost.

A further nine NMCs in Africa and the Middle East have been requested by WMO to participate in FGGE during the Build-up Year and the Operational Year, and although only a few observations are expected from each NMC, any data sent to Bracknell will help increase the amount of delayed data collected.

One RTH has begun to send a collective on magnetic tape at monthly intervals. Although many extra observations are obtained in this way, the collective does not include all observations for the area which have been received on paper tape.

ACKNOWLEDGEMENTS

The authors wish to thank the following for their valuable assistance in planning and carrying out this project:

GARP Activities Office, WMO, especially Dr Boldirev; contributing NMCs in Europe, Africa and the Middle East; Foreign and Commonwealth Office.

The assistance of several branches of the UK Meteorological Office, in particular the team who performed similar work for GATE is also gratefully acknowledged. The special computer programs were mostly written by C. Long. The following cheerfully assisted with the bulky and sometimes tedious work of dispatching postal boxes and reading in paper tapes: D. Green, Mrs A. Saunders, and Mrs A. Jackson.

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THE MEASUREMENT OF FOG ON MOTORWAYS

By H. A. DOUGLAS (Meteorological Office, Bracknell*), D. J. JEFFREY (Transport and Road Research Laboratory, Crowthorne) and F. JEZZARD (Police Scientific Development Branch, Home Office, London)

SUMMARY

The Meteorological Office, the Transport and Road Research Laboratory and the Home Office have combined in a trial to evaluate potential low-cost visibility instruments as possible aids in motorway traffic control. The results of the trial show that the two instruments under test came close to the performance criteria laid down before the trial but that each had limitations. The short-baseline transmissometer showed a temperature drift which was sufficient to give an apparent visibility change of 7 m $°C^{-1}$ (at 200 m), and the forward-scatter instrument gave poor results when obscuration was caused by factors other than fog (for example precipitation or spray).

INTRODUCTION

A series of multiple crashes on motorways, in fog conditions, during the late sixties and early seventies, led to the appropriate authorities considering the use of instrumentation to help reduce the incidence and costs of such accidents (a single multiple accident has been estimated to cost £0·5 million, excluding the cost of suffering and bereavement (Transport and Road Research Laboratory (TRRL), 1972a)). The Home Office originally considered the use of an

* Now at Meteorological Office, RAF Strike Command, High Wycombe.

instrument which would assist the police in cases of prosecution for driving dangerously fast for the prevailing visibility conditions. This was soon shown to be impracticable, and the emphasis shifted to providing relatively low-cost instrumentation to give advance warning of the visibility ahead. The Transport and Road Research Laboratory were interested in the effects of fog on driver behaviour and traffic flow parameters. Also the appropriate authorities wished for detailed forecasts, on a time-scale of one to two hours, of the visibility to an accuracy better than 20 per cent over the entire length of a motorway and for estimates of how the visibility would change with time. The Meteorological Office became involved in 1972 when it advised both groups that it was not realistic, even with the aid of instruments, to expect such accurate forecasts of the distribution or density of fog.

The three organizations then agreed to co-operate in a trial which had the aims of identifying and establishing some of the relevant details of instrument performance, traffic flow parameters and police control procedure. The trial, using a length of the M4 motorway near Reading, took place between February 1974 and June 1976. Each organization sought different information, and this paper summarizes the results from the trial of two relatively low-cost instruments designed to measure the visibility.

A description of the site and the instruments is followed by a discussion of the results.

Experimental details and description of the instruments

The particular aims of the experiment, described in this paper, were: (1) the evaluation of the accuracy of different visibility-measuring techniques, and (2) to determine whether instruments will continue to operate successfully over long periods when left unattended at the roadside.

To provide the necessary data for these aims to be achieved, three compounds were erected alongside the eastbound lane of the M4 motorway, between Theale and Reading. This site was chosen since TRRL had already started to instrument the site and it was known to be a fog-prone area, being low-lying and adjacent to gravel pits. All the compounds housed one of each type of visibility instrument on trial, whilst the central compound also contained a modified Meteorological Office Transmissometer (MOT), for use as a reference instrument, and various other meteorological instruments (see Plate I). The MOT (Meteorological Office, 1971) measures the optical transmission (T) of a horizontal beam (d km long) of light through the atmosphere. The transmission is related to the extinction coefficient (σ) and thence to the visibility (V) by Koschmieder's equation

$$V = 2{\cdot}9957/\sigma \text{ km},$$

where $\sigma = d^{-1} \ln T^{-1}$. For this trial, the support structure was modified to allow the beam to be at a standard height of 1·3 m above the road surface, and the baseline was reduced from 200 m to 100 m. The effect of reducing the baseline was to change the operating range of the instrument from 100 m–20 km to 50 m–10 km. The output from the transmissometer was exponentially smoothed with a time-constant of 40 seconds. Before installation on the motorway, the instrument was compared with a standard transmissometer and it was confirmed that the alterations had not affected the response.

Two measuring techniques were under trial; the first, similar to that employed by the MOT, measured the ratio of received light to transmitted light. The difference was that the instrument in the trial used a folded-path technique with an effective path length of 4 m. This allowed for measurements of visibility down to 10 m but with an effective upper limit of 200 m. An instrument (TRRLT) designed at the Transport and Road Research Laboratory (TRRL, 1972b and 1974) was used to represent this technique (see Plate II). In this particular instrument, the initial beam is split—one path passing through the atmosphere and the second being totally enclosed. This allows the compensation circuit for lamp fluctuations to be self-contained. The outputs from the two matched detectors are compared, the difference in their values being a measure of the atmospheric attenuation or extinction coefficient (σ). The output was again exponentially smoothed with a time-constant of 40 seconds.

The second technique was that of forward scatter. A Point Visibility Meter (PVM), (Winstanley and Adams, 1975), developed by Plessey Radar Ltd under a Home Office contract, was the instrument used to represent this technique. The instrument (see Plate III) measures the light scattered at a specific angle ($\approx$34°) in the forward direction of the beam. The angle was selected so that dependence on particle size was minimized and thus it can be assumed that the intensity of the received light was proportional to the extinction coefficient (σ). An exponential smoothing circuit was applied to the output. This had a time-constant of 120 seconds, the longer time being intended to compensate in part for the much smaller sampling volume of this instrument.

During the trial, the MOT was regularly serviced, cleaned and calibrated, whilst the other visibility instruments were left untouched. Data from all the instruments were telemetered every 15 minutes to TRRL where they were recorded in a computer-compatible form. When the visibility, as indicated by the MOT, dropped below 800 m, data from the instruments were recorded on punched paper tape, every 2 minutes, at the motorway site. The analysis described in this paper was carried out by the Meteorological Office, after copying the original data both from the magnetic tapes and from the paper tapes, and principally covers the period of the first full winter, November 1974 to May 1975.

RESULTS

(1) *General*

Clearly an important feature of any instrument which is intended to operate in a roadside environment over a long period of time is the stability of its calibration. The changes in calibration could arise from many causes, but one of the principal problem areas is the cleanliness of the optical surfaces. To identify any such shift, two periods were chosen (one near the beginning and one near the end of the trial period) for which the MOT gave similar values, and where the temperatures were the same (see later). The mean values of the outputs of the TRRLT and the PVM were calculated and Table I lists the results. The changes in calibration—equivalent to a zero shift—are given in terms of a change in recorded visibility for a true visibility of 200 m. The changes of 123 mV (TRRLT) and 111 mV (PVM)—obtained from the values in column (c) of Table I by subtracting the 2 mV change in the mean output of the MOT—would give an apparent visibility change of 46 m and 9 m respectively. To identify any drift in calibration related to temperature, all occasions for which the MOT (which

TABLE I—COMPARISON OF MEAN VALUES OF OBSERVATIONS TO CONSIDER CALIBRATION DRIFT (TEMPERATURE LIMITS 3 °C TO 6 °C)

	a 17 Nov. 1974	b 11 May 1975	c Difference (a—b)	Visibility*
	Mean voltage output of instrument			
MOT	9·475	9·473	0·002	0·1 m
TRRLT	0·188	0·063	0·125	46 m
PVM	0·176	0·063	0·113	9 m
No. of readings	6	8		

* The value in column (c) expressed in terms of visibility for a true visibility of 200 m.

has a negligible temperature coefficient) indicated a visibility of between 6·5 km and 7·0 km were extracted, and regressions of the temperature and the outputs of the TRRLT and PVM were calculated. This range was selected so that within the range there should be no measurable change of output in either the PVM or the TRRLT. The correlation coefficient ($r = 0{\cdot}094$, $N = 73$) in the case of the PVM showed the effect to be negligible. In the case of the TRRLT there was a significant relationship which would give a temperature coefficient of 7 m $°C^{-1}$, at 200 m.

The well-known variability of fog restricted these instrumental comparisons to data recorded from the central compound. The Meteorological Office is also using the data recorded from all three sites, with a view to establishing the spatial and temporal variations which do occur. This investigation will be reported elsewhere.

To aid comparisons, made difficult by differences in path length, time-constants, and physical principles, the rate of change of visibility (defined in terms of the MOT value) was calculated for each data point and the comparisons were made both for the whole data set and for the 'reduced set' in which the visibility was changing only slowly (less than 20 m min^{-1}). The usual form of comparison was a scatter diagram with the associated regression equation and correlation coefficient. Two such diagrams are presented as Figures 1 and 2.

Figure 1 illustrates the 'reduced set' of data for the PVM, within the limited range of 50 m to 1 km, whilst Figure 2 gives the corresponding scatter plot for the TRRLT over the range of 50 m to 200 m.

The TRRLT and PVM comparisons are now considered separately.

(2) *Point Visibility Meter* (*PVM*)

This instrument functions by using the forward scatter of light, and the scattering function, and hence the indicated visibility, is dependent on the particle size, although the forward angle has been selected to minimize such an effect. Thus, unlike the MOT, the PVM would give a different signal level for, say, snow and fog even when the optical attenuation in the atmosphere was the same. The calibration equation provided by the manufacturer is designed to measure fog. Unfortunately it was not possible to separate completely the data relating to fog from those relating to other obscurants although it could be seen that many of the points exhibiting large deviations from the expected value came into the latter category. A parallel investigation by the Meteorological Office has confirmed this dependence on the actual conditions causing the atmospheric attenuation, and this work will be reported more fully at a later date.

The PVM has a very small sampling volume (roughly a cube of sides 10 mm) and the increased time-constant compared to that of the transmissometers is only a partial compensation for this feature. The comparison of instrument performance between the MOT and the PVM should thus be under as uniform conditions as possible to limit effects due to spatial variations of visibility and thus the 'reduced set' of data was used (Figure 1). The resulting regression was

$$Y = 0{\cdot}802M + 19{\cdot}52 \quad (r = 0{\cdot}92,\ N = 840),$$

where Y and M are the visibilities as measured by the PVM and MOT respectively, r is the correlation coefficient and N the number of relevant points. This

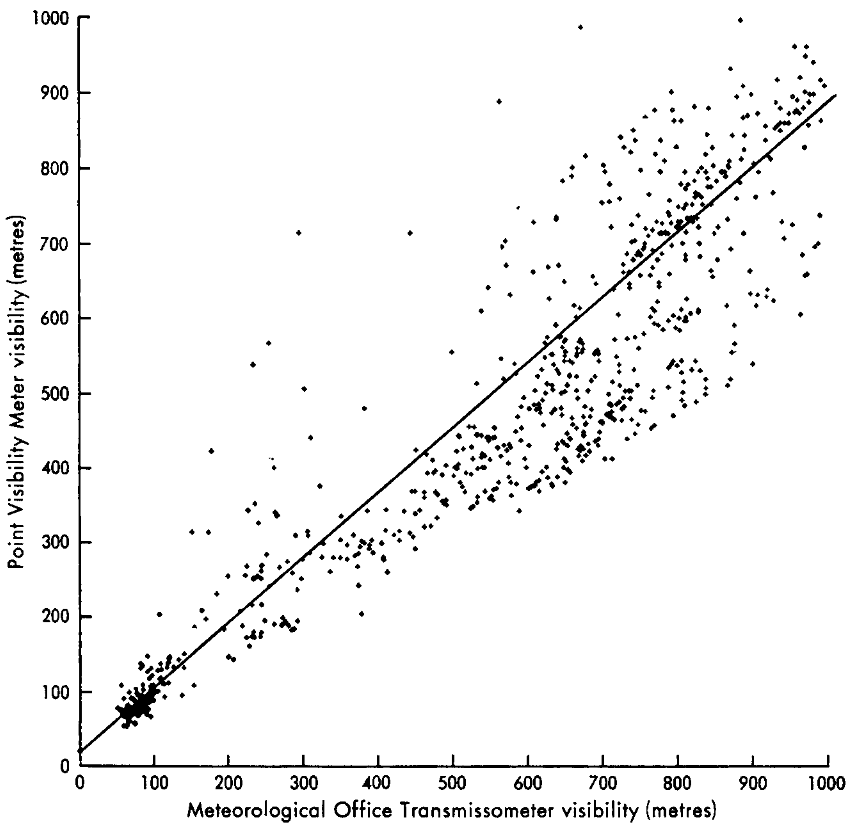

FIGURE 1—SCATTER PLOT, WITH ASSOCIATED REGRESSIONS, SHOWING THE COMPARISON BETWEEN VISIBILITIES AS INDICATED BY THE POINT VISIBILITY METER (Y) AND THE METEOROLOGICAL OFFICE TRANSMISSOMETER (M), IN STEADY CONDITIONS (RATE OF CHANGE $\leqslant$20 m/min) AND WITHIN THE RANGE 50–1000 m

Equation of regression line $Y = 0{\cdot}802M + 19{\cdot}52$
Correlation coefficient $r = 0{\cdot}916$
Number of observations $N = 840$

regression should be considered as the best estimate in fog conditions over the range 50 m to 1 km. Using this regression to give the value of Predicted (PVM) visibility in the formula

$$\text{Error} = \frac{(\text{Observed (PVM)} - \text{Predicted (PVM)})}{\text{Actual (MOT)}} \times 100 \text{ per cent}$$

gives a mean error of 1·5 per cent and a standard error of 20 per cent over the above range. Over the limited range of 50 m to 200 m, the corresponding figures are 0·3 per cent and 20 per cent.

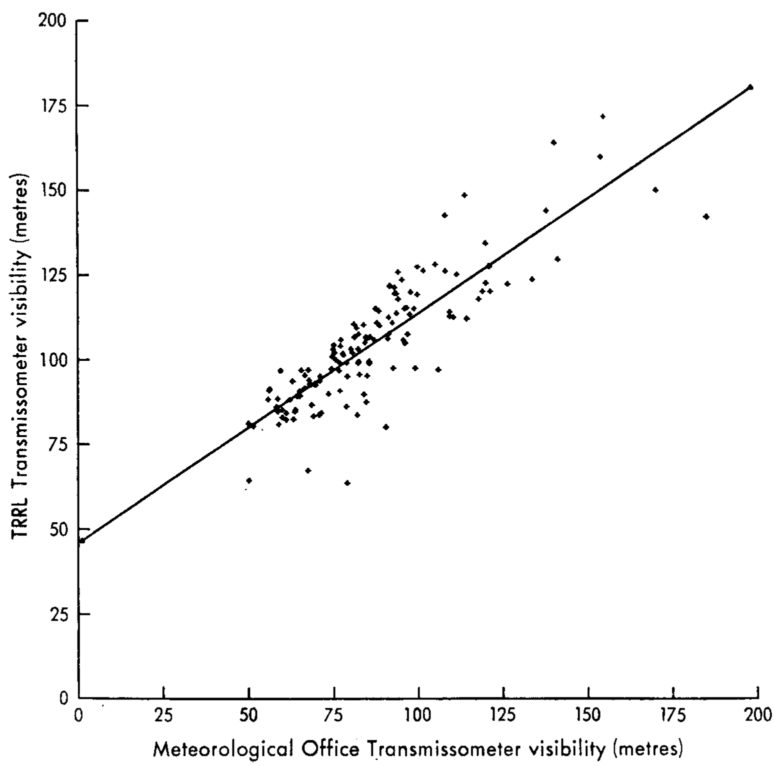

FIGURE 2—SCATTER PLOT, WITH ASSOCIATED REGRESSIONS, SHOWING THE COMPARISON BETWEEN VISIBILITIES AS INDICATED BY THE TRANSPORT AND ROAD RESEARCH LABORATORY TRANSMISSOMETER (Z) AND THE METEOROLOGICAL OFFICE TRANSMISSOMETER (M), IN STEADY CONDITIONS (RATE OF CHANGE $\leqslant$20 m/min) AND WITHIN THE RANGE 50–200 m

Equation of regression line $Z = 0{\cdot}670M + 47{\cdot}36$
Correlation coefficient $r = 0{\cdot}860$
Number of observations $N = 142$

(3) *Transport and Road Research Laboratory Transmissometer* (*TRRLT*)
The physical principle utilized by this instrument is independent of the particle size problem encountered with the PVM. The main difference between the TRRLT and the MOT is the difference in path length, and thus its representativeness of the general visibility. For the data shown in Figure 2, the regression over the range 50 m to 200 m was

$$Z = 0{\cdot}670M + 47{\cdot}36 \quad (r = 0{\cdot}86,\ N = 142),$$

where Z is the visibility as measured by the TRRLT, the other symbols having the same meaning as for the PVM case. The associated mean and standard errors, within the range 50 m to 200 m, were 0 per cent and 11 per cent respectively, and these should be compared with the second set of figures given for the PVM. The lower error figures for the TRRLT, compared with the PVM, are due to the relative independence of particle size of the transmissometer principle, but it should be remembered that 200 m is the effective upper limit to the range of this instrument.

(4) *The 1975/76 winter*
The trial again took place throughout this period, but technical problems, combined with a very low incidence of fogs, meant that few additional data were obtained. These data have not been fully processed, but the initial calculations indicate a similar result to that for the first winter. Table II lists the corresponding full data regressions for each instrument for each winter.

TABLE II—COMPARISON OF REGRESSION EQUATIONS OVER THE TWO WINTERS

	Winter 1974/75	Winter 1975/76
TRRLT for range 50 m–400 m	$Z = 0{\cdot}636M + 59{\cdot}91$ ($r = 0{\cdot}787$, $N = 385$)	$Z = 0{\cdot}627M + 75{\cdot}27$ ($r = 0{\cdot}804$, $N = 28$)
PVM for range 50 m–1 km	$Y = 0{\cdot}670M + 68{\cdot}61$ ($r = 0{\cdot}838$, $N = 1442$)	$Y = 0{\cdot}532M + 152{\cdot}27$ ($r = 0{\cdot}670$, $N = 66$)

CONCLUDING REMARKS

The trial has indicated the potentials and limitations of two types of instrument. Both are able to withstand exposure to a roadside environment. One, based on transmission, illustrates the disadvantage of a range limited by its effective baseline whilst the second, based on forward scatter, gives different responses under different conditions. Standard errors of 11 per cent and 20 per cent respectively over the range 50 m to 200 m, common to all instruments, have been established, and with this knowledge the two user authorities are continuing their own investigations into the most appropriate low-cost visibility instrument. The Home Office have established a prototype network on part of the M1 motorway to provide real-time data to the Police and to evaluate the benefits of such a scheme. TRRL are continuing to use the M4 site to establish relationships between traffic parameters, driver behaviour and visibility. The trial has given the Meteorological Office further experience of two instruments which could be considered as visibility instruments for sites where a 200 m baseline is impracticable.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the help and advice of colleagues associated with this project and thank the Thames Valley Police for their assistance with the running of the trial.

REFERENCES

Meteorological Office	1971	Transmissometer Mk 3A, Mk 3B and Prototype Mk 4 Operator's Instructions.
Transport and Road Research Laboratory	1972a	Fog and road traffic. *Transport and Road Research Report* LR446.
	1972b	A low-cost fog detector developed for use on roads. *Transport and Road Research Report* LR453.
	1974	Detection of degree of opacity in light paths. *Provisional patent* 24178/74.
WINSTANLEY, J. V. and ADAMS, M. J.	1975	Point visibility meter: a forward scatter measurement of aerosol coefficient. *Appl Optics*, **14**, No. 9, pp. 2151–2157.

551.5:621.391

METEOROLOGICAL OFFICE PARTICIPATION IN PRESTEL— THE POST OFFICE VIEWDATA SYSTEM

By J. PARKER
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SUMMARY

Prestel and teletext are discussed. These new information media use domestic television receivers as visual display units. In this review particular reference is made to their relative merits and their importance to the Meteorological Office.

INTRODUCTION

June 1978 saw the start of the test service of the Post Office viewdata system known as Prestel. Since the Meteorological Office is participating in the test this is an appropriate time to review the system, together with the complementary information medium, teletext. Both are important new developments in the communications field providing relatively cheap visual displays of information from data banks which are accessed by very simple techniques. The visual presentation allows efficient assimilation and the ease with which the data can be accessed makes the potential size of the body of users very large.

COMPARISON BETWEEN TELETEXT AND VIEWDATA

Since both systems are relatively new communications media it is worth while spending some time looking at their similarities and differences. At first sight they may seem to be alike and essentially competing, but in fact this is not so. The basic similarity is that they both use a suitably modified domestic television receiver to display, on demand, information stored in a computer. The electronic modifications to the television set, and the display format, are essentially the same for both systems so that each can be displayed on the same receiver. However, the methods used to transfer the information from computer to television set are fundamentally different.

Teletext is the system developed by the broadcasting authorities, the BBC version being better known as Ceefax and that of the IBA as Oracle. Although they were developed independently, a single standard was agreed upon and has been in use since 1974. Teletext is made possible by the need for some blank lines in the normal television signal to allow time for the scanning beam in the receiver to return to the top of the screen. These blank lines are used to transmit digital representations of information as part of the broadcast signal. The modified electronics of the receiver then extract the teletext portion, decode the signal and display the information on the screen instead of the normal picture. Viewdata has been designed by the Post Office, who have adopted the trade name of Prestel. It achieves the same display by means of a simple conversion to a domestic telephone. In this way data can be sent between computer and television receiver along ordinary telephone lines. This means that instead of information being broadcast for anyone to use, the data bank is interrogated at the initiative (and usually at the expense) of the user. Not only does this give a new means of communicating information, but it also allows for more efficient use of the existing public telephone network.

This one basic difference has many consequences. For example, teletext is available only during broadcasting hours, whereas Prestel provides a 24 hour service. Perhaps of more importance is the fact that the information disseminated by teletext is under the ultimate control of the appropriate broadcasting authority. With Prestel the responsibility for the content of the information remains with the 'Information Provider', the Post Office merely supplying the means of communication. This is a significant point with regard to the Meteorological Office participation. As a contributor we have an editing facility and information can be updated immediately, as and when required (see Plate VI). There is also an important financial comparison. Access to teletext information is free because of its broadcast nature, but Prestel will cost the user the price of a local telephone call at least, and the Information Provider has the option of adding a charge for the information on display. On this basis teletext is the more attractive system for the user. However, the virtually unlimited capacity of Prestel gives it an overwhelming advantage. The capacity of the teletext system is limited by the number of spare lines available within the television signal. At present Ceefax and Oracle each make use of only two lines. This provides for display an absolute maximum of 800 frames, one frame being effectively the amount of information that can be displayed on the screen at one time. In practice the capacity is reduced as a result of the method of transmission. The entire content of the data bank is broadcast in a cyclic manner, which means that there is a significant time-lag between frame selection and frame display, its length depending on the total number of frames in the sequence. It takes roughly 24 seconds to transmit 100 frames, so that on selecting a frame from a 100 frame sequence there will be an average delay of 12 seconds before display. To keep this delay to a tolerable minimum considerably less than the maximum number of frames are in fact used. Since Prestel is accessed directly, any frame can be selected and displayed in about 2 seconds, and the capacity of the data bank is limited solely by the amount of storage available to the computer. After using Prestel, information seekers are likely to find the delay inherent in teletext trying. For the test service Prestel will have in the region of 100 000 frames available for use. This allows for a fairly comprehensive coverage of information to be provided. Ideally a user should be able to gather from various parts of the data bank all the information he needs on a particular subject. For example, as well as the average weather conditions for a holiday destination he should be able to find out the times of the best form of transport, hotel facilities, package tour operators and sources of entertainment.

The relative sizes of the data banks, and the different access methods, result in a fairly well-defined distinction between the type of information held on each system, which in turn explains their complementary nature. A broadcast system has the advantage that all users are able to select the same item of information simultaneously from the relatively small data bank. Prestel's much larger data bank, however, can only be used by a fraction of the population at one time because there must be a finite number of access points to the computer. Thus teletext is better qualified to transmit the sort of information that many people want to see simultaneously, such as the latest news. Prestel on the other hand is best suited to hold large quantities of long-period reference data and information tailored to specialized interests. Naturally there is a certain amount of overlap between the two systems, but clearly, they both have a place in the field of mass communication.

The final and perhaps most crucial difference, however, is that Prestel is an interactive system. Since there is a two-way link between user and computer, each can respond to the requirements of the other, and the user can make fuller use not only of the data bank but also of the capabilities of the computer itself. This has many implications for the future which will be discussed later, but it also means that there is a difference in the way that teletext and Prestel are used.

How to use teletext and Prestel

Both systems work on the principle of identifying frames by number. A particular frame can be displayed by entering its number on a hand-held keypad (see Plate VI). Teletext uses three-figure numbers which are listed on several known index frames. Selecting a number causes the frame to be displayed when it is next broadcast in the sequence, and it is held on the screen until another frame is chosen. Prestel frames can be selected in a similar manner, but since the data bank is so much larger, up to nine digits are used for frame identification. This method of access is perfectly acceptable to someone knowing the reference to a required frame since the display is almost instantaneous. However, it was realized from the beginning that for Prestel to succeed it would have to appeal to all types of user, from the domestic level with no experience of dealing with computers to someone in the business world with little time to cope with elaborate access procedures, and therefore it had to be simple to use. To achieve this Prestel is structured on the basis of a selection tree, each branch giving access to a different classification of information. In essence, a user is presented with up to ten options on early frames in the structure, and progresses by keying a single digit on the keypad according to his choice. This procedure is followed until the required information is displayed. Equally simple instructions allow a user to retrace his path over the previous three frames he has viewed, and also to correct keying errors. As a further aid the Post Office recommends to all Information Providers the practice of including 'prompts' on all frames, that is to say, advice on what needs to be done as the next step.

Display format

Plate IV illustrates the Prestel display format and the facilities available as design aids so that information can be presented in an attractive fashion. As explained earlier the teletext format is essentially the same. The screen has 24 lines, 22 of which are available to the Information Provider, the top line being reserved for Post Office information and the bottom line for messages from the computer. Each line has 40 character positions. All standard keyboard characters are available, but in addition each character position can be divided into six squares, any combination of which can be displayed at that position. This gives the facility of building simple illustrations, and has enabled the Post Office to provide a bold graphics typeface, which can be used for the automatic construction of headlines, for example (see Figure 1). They have also provided a choice of colours which they describe as red, yellow, green, blue, magenta, cyan (pale blue) and white, plus a facility that enables any group of characters to flash on and off at regular intervals. The display format has been designed to present the maximum information that can comfortably be read on a television screen, and thus underlines a fundamental editing problem that faces the Information Provider. To keep the cost to the user down to an acceptable minimum, as much information as possible should be displayed on one frame. At the same time the overall appearance of the frame should be attractive, clear, and easy to read.

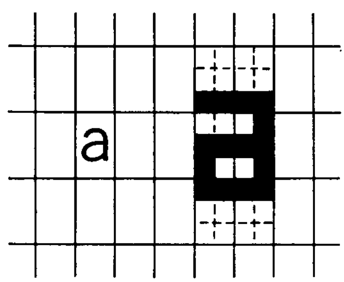

FIGURE 1—ILLUSTRATION OF STANDARD TYPEFACE AND GRAPHICS TYPEFACE

The constraint of 40 characters per line, however, means that an average line of text from this page of the *Meteorological Magazine* would occupy two lines on a Prestel screen. Furthermore, a heading using the graphics typeface takes three lines. Consequently a certain style of presentation has to be adopted to give the maximum amount of information with the minimum number of words. Not only that, but consideration must also be given to the appearance and readability of the information in terms of layout and colour.

The test service

A test service is at present being jointly run by the Post Office, television manufacturers and numerous Information Providers, all of whom are interested in the potential of a full public service. For the trial about 1500 Prestel user terminals are being made available to a selection of people in London, Norwich and

Birmingham. As an Information Provider the Meteorological Office has an editing terminal located in the Central Forecasting Office under the control of the Public Services Branch, which is used for entering, and updating as necessary, a selection of meteorological information (see Plate V). At present this terminal consists of a television receiver and an editing keyboard (see Plate VI). It is envisaged that in the future there will be a need for an 'intelligent' terminal with a microprocessor and its own local storage. In this way a batch of editing can be carried out locally without being connected to the Prestel computer, the telephone link only being used to send the completed frames. It will also be possible for some of the updating to be done directly using a computer-to-computer link.

For the purpose of the test service the Meteorological Office is providing a wide range of meteorological information. Forecasts are naturally of prime importance, and range in scope from a broad forecast for the United Kingdom as a whole to forecasts tailored for particular activities and localities. However, actual weather conditions and climatological averages are also of great interest and importance to a wide variety of people, and a selection of each is included within the section of the data bank allocated to the Meteorological Office. Prestel also affords the opportunity to advertise the full range of the consultancy services of the Office. By contrast, the range of meteorological information that can be displayed by teletext is severely limited and must be of a much more general nature. Since the contribution of the Meteorological Office to Prestel is fully under its editorial control the test service will be used to experiment with the proportion of space allocated to each type of information, and also the layout and content of the various frames. In this way it is hoped to ensure that the service is as suitable as possible for the user.

FUTURE APPLICATIONS OF PRESTEL

To demonstrate further the importance of the interactive aspect of Prestel it is perhaps worth while listing some of the potential applications. Primarily of course it provides a centralized information service, not only in terms of actual stored information but also by acting as a first reference point in a wider search for information. Teletext can also fulfil this function to some extent, although the volume and content of information differ considerably. However, Prestel can go one step further and act as an intelligent interface with specialist data banks on remote computers belonging to other organizations. It can translate the requirements of the user according to the protocol and language of the appropriate computer, locate the information and then transmit it to the user's terminal. The Prestel computer can also be used by individuals to store their own information, whether it be facts and figures or favourite recipes. Furthermore, since messages are no more than units of information, Prestel can act as a communication device, storing and sending messages to individual terminals. This of course extends the use of the telephone to the deaf. Some of the information stored in the system could well be in the form of advertisements—jobs, property, services, rentals, wanted and for sale—which could be responded to immediately via Prestel. Programmed learning is a natural application of such an interactive system, not only in terms of formal education in schools using pre-recorded video cassettes but also in the home. Prestel can also provide a calculator service which can bridge the gap between pocket calculator and powerful computer. In the same way that goods could be bought and sold in response to advertisements, so reservations could be made for hotels or holidays. Prestel can even contribute to the field of entertainment in the form of jokes, quizzes and games.

In the future the communications aspect of Prestel could be of great importance to the Meteorological Office, with the advent of compatible hard-copy printers and video cassettes. Given the facility of forming 'closed user groups' where only members of the group can access a certain part of the data bank, private messages can be sent within a group. Outstations with editing terminals will then have an alternative means of communication, not only within the Meteorological Office, but also with any known subscriber to Prestel. The message switching capability of the Prestel computer can then be used, for example, to deliver warnings to customers on a semi-automatic basis.

Conclusion

Prestel is an example of a new concept in information media with an immense information capability and potentially far-reaching impact on telecommunications and society. It is the result of bringing together the best features of several technologies—large-scale integration in the receivers, optimized software in modern, fast, real-time computers, simplified data structures and computer access protocols—each aspect designed to ensure that the general public will be as much at home in using this new medium as it is now in using the telephone. As such it is ideally suited to provide a valuable aid in the dissemination of meteorological information, as well as being a potential source of substantial revenue for the Meteorological Office.

Acknowledgement

I am indebted to colleagues in the Public Services Branch of the Meteorological Office for helpful suggestions and encouragement in producing this article.

REVIEW

Environmental Aerodynamics, by R. S. Scorer. 240 mm × 155 mm, pp. 490, *illus*. Ellis Horwood Limited, Publishers, Chichester, 1978. Price: £20.00.

On the dust cover we are told that this book is an entirely rewritten successor to *Natural Aerodynamics*. The readership is intended to be wide, ranging from civil and mechanical engineers through applied mathematicians and physicists to aerobiologists and ecologists. The fact that the subject matter has largely been drawn from the content of two lecture courses which Professor Scorer has given to students at Imperial College contributes to both the strengths and the weaknesses of the book.

A glance at the first two chapters, on fundamental equations and the phenomena of fluid flow, will warn the reader that this book is pitched at a very different level from that of its predecessor. Right from the start there is a no-nonsense assumption of postgraduate mathematical fluency, although this is tempered by a liberal supply of examples of applications of the theory in nature. This distinguishes it from most texts on dynamical meteorology, which rarely delve into the subject in detail and leave the student with a wide gap to traverse before reaching the level of current research, but it may discourage the non-mathematician. In the third chapter the subject of secondary vorticity (a favourite one of Professor Scorer) is examined in depth, but the chapter on the effects of the rotating earth is a disappointing contrast. It is difficult to accept that our understanding of baroclinic systems has not progressed from Sutcliffe's development theory, and in view of the role of fronts in controlling the level of environmental pollution it would have seemed appropriate in a book with this title to extend the discussion of frontal dynamics beyond that of Margules. A reference to rotating annulus laboratory experiments and to modern studies of frontal structure might not have been out of place, but evidently these topics do not figure prominently in the author's lecture courses. On the subject of waves in stratified fluids, however, he is back in his element and gives an extensive up-to-date review, though personal opinion has a tendency to supplant objective discussion in some places (the sizeable literature on critical layer absorption is dismissed in a single paragraph as being speculative and based on incomplete mathematics).

The second part of the book, on turbulent phenomena, clouds and dispersion, is necessarily more descriptive. The chapter on partly turbulent flow is largely concerned with buoyant convection and jets as determined by laboratory experiments, while in the subsequent chapter the author considers examples of similar effects in the atmosphere. The subject of dispersal of pollution really requires a book to itself, but Professor Scorer manages to compress it into a single chapter by concentrating attention on dispersion from point sources near the ground. The chapter on clouds and fallout is concerned with the principal dynamical processes leading to different cloud forms. This is a topic on which the author has written several books and papers and here he has given a concise account linking theory and observations, but the inclusion of a section on the dynamics of atmospheric tides seems out of place. The book tails off a bit towards the end with a chapter which attempts to cover the aerodynamics of aphids, swallows, cuckoos, vultures, buzzards, albatrosses, locusts and pest swarms, but does so in such an insubstantial way that it seems barely worth including. The same can be said for the epilogue entitled 'Making peace with nature'. The examples for discussion at the end are mostly reworded versions of those in the earlier book, but they are as thought-provoking now as they were 20 years ago.

Professor Scorer is an acknowledged master of the art of attractive presentation and this book is an excellent example of his skills. The theoretical arguments are illustrated by clear uncluttered diagrams and by a large number of superb photographs, all of which are relevant to the text and not just included for their pictorial quality. The enthusiasm of the author is communicated to the reader throughout the book but the style resembles that of a verbally delivered lecture, and ideas, assumptions and approximations are introduced so thick and fast that at times one wishes it were possible to stop the author and ask a question. Sometimes there is some confusion so that a prior knowledge is really required in order to appreciate the argument (such as on page 219 where the symbol beta is used for two totally different physical quantities within the same sentence), while at other times the author's novel viewpoint gives new insight into the subject.

This book is not a comprehensive text on dynamical meteorology but an account covering the broad interests of a leading scientist. Those who browse through it will find a great deal to attract their attention, but I doubt if the genuine readership will be as widespread as that of its classic predecessor *Natural Aerodynamics*.

P. W. WHITE

Note added in proof: A paperback edition of this publication is also available at £7.50.

THE METEOROLOGICAL MAGAZINE

NO. 1273 AUGUST 1978 VOL. 107

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

Dd. 595890 K15 8/78 ISBN 0 11 724802 9
ISSN 0026–1149

Met.O.915
METEOROLOGICAL OFFICE

the meteorological magazine

SEPTEMBER 1978 No 1274 Vol 107
Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.915

THE METEOROLOGICAL MAGAZINE

No. 1274, September 1978, Vol. 107

551.501.9:551.508.77(425)

AN INVESTIGATION INTO RAINFALL RECORDING AT OXFORD

By J. M. CRADDOCK (Climatic Research Unit, School of Environmental Sciences, University of East Anglia)

and

C. G. SMITH (School of Geography, University of Oxford)

SUMMARY

An account is given of the rainfall records in Oxford since the 18th century with special reference to the work of the Radcliffe Observatory (since 1935 the Radcliffe Meteorological Station). A comparison made between measurements from five different rain-gauges in the years 1868–1907 serves to illustrate the potential value of the Oxford record and to reveal some problems of a kind likely to be encountered when more than one gauge has been in use at the same site over a long period.

1. INTRODUCTION

After the record of Oxford weather made by Dr Richard Plot in 1684 the next impetus towards meteorology came from Dr Thomas Hornsby (1733–1810). This remarkable man who, like many of his 18th century contemporaries, held a number of university offices in plurality, became Savilian Professor of Astronomy in 1763 and, as the first Radcliffe Observer, supervised the construction of the Observatory from its foundation in 1772 until its completion in 1794. Hornsby's own rainfall record over the period 1760 to 1805 is not complete and has been the subject of another paper (Craddock, J. M. and Craddock, E., 1977). Some accounts of the rainfall record made by his successors at the Observatory from 1815 onwards have been published by Smith (1969, 1974 and 1975). For the period from 1815 to 1930 these rely entirely on the homogeneous series of monthly rainfall totals published by Knox-Shaw and Balk (1932) which attempts to provide definitive estimates of Oxford rainfall for the months considered. As part of a larger investigation, one of us extracted the records of Oxford rainfall which had been sent to the British Rainfall Organization during the last century, and which are now in the 10-year books which form the main rainfall archives of the Meteorological Office, with the object of using these to obtain numerical evidence of the relationships holding between measurements made at nearby sites. However, there were some disagreements between apparently authentic records, and it was the elucidation of these differences that brought us together. The number of different rain-gauges in use at the Observatory during part of the 19th century and the fact that many of the monthly and daily totals have been published in *Radcliffe Observations*, either annually or quinquennially, prior to the Knox-Shaw and Balk summary to 1930, renders the use of the published and unpublished figures for particular gauges a difficult task and one liable to erroneous interpretation. Much information on the nature and precise siting of the rain-gauges is available in the publications of the Observatory, and other essential information is available in the original manuscript records and observing books held at the School of Geography. However, a few vital pieces of information required considerable research in Oxford libraries and it is possible that some vital scraps of information have been lost or destroyed. The present paper attempts to summarize the facts about the Radcliffe rainfall record, in so far as these can be determined, for the benefit of future investigators, and also makes some comparisons between that record and another Oxford record, which has often been quoted, namely the one maintained at the Botanical Gardens between 1870 and 1953. Initially the record was maintained by a Fellow of Magdalen College and the record has been listed and described as Oxford, Magdalen College.

2. Historical

The history of rainfall measurements at the Radcliffe Observatory is illustrated in Figure 1, which is a sketch based on the 1895 Ordnance Survey Plan of Oxford at a scale of 50 inches to the mile. The Observatory building is unchanged from the time of Hornsby, apart from a small addition to the tower in 1857 to enable meteorological observations to be made there. At the time of writing these Victorian additions are being removed and the tower restored to its original appearance. The surrounding wall on the north side and the adjoining observer's house date from the same period. Figure 1 shows the surroundings as they were for most of the period from 1815 to 1895, although some important changes, described later, have taken place in the present century on the south side of the building. The foundation of the Observatory has been described by Smith (1969) and further facts can be found in Gunther (1923) and in the article on Hornsby in the *Dictionary of National Biography*. The present account mentions only points which affect the observation of rainfall. Hornsby's early rainfall record has been described elsewhere (Craddock and Craddock, loc. cit.) and it seems that after 1775 this was taken at the Observatory. It was this original roof gauge, read intermittently for brief periods between 1806 and 1814, that became the main Radcliffe record from 1815 until 1851. The original gauge was sited 22 ft 6 in. above the ground on the roof of the east wing of the Observatory; it was level with the parapet on the north side of the building and at a distance of 31 ft 8 in. from the central balcony platform of the Observatory from which the tower rises (Rigaud, S. P., *ca* 1834 and 1835). Since then the record has been continued with different rain-gauges and some changes of site until the present day. In all at least seven individual rain-gauges have been used and apart from the period from January 1816 to December 1833, when readings were taken at irregular dates, the gauges have been read daily. However, the hour of observation has varied and there were never more than four gauges in use at one time. During the period when the gauges were read at irregular dates there was no consistent pattern in the intervals between readings. Sometimes the gauge was read two or three times a month and sometimes two or three times a week, depending on the distribution of rainfall.

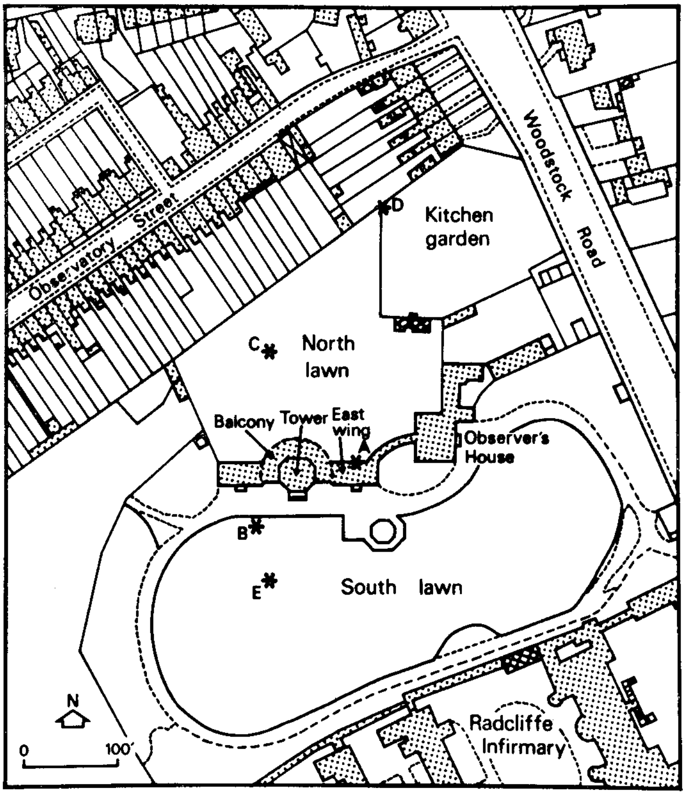

FIGURE 1—PLAN OF THE RADCLIFFE OBSERVATORY AND THE IMMEDIATE VICINITY IN ABOUT 1895

From 1815 until early 1850 there was only the east wing roof gauge. From 1851 until early 1862 there was also a ground gauge, and from then until the end of 1907 four gauges were in simultaneous use. Then the number fell to three, and at the end of 1908 to two. Between 1923 and 1930 the original east wing roof gauge was revived to provide direct comparisons with the modern ground gauge then in use. In 1963 the two remaining gauges, a Beckley siphoning self-recording gauge and an 8 in. gauge, were replaced by a modern tilting-siphon gauge (then known as a 'Dines') and a 5 in. Meteorological Office pattern gauge. The Beckley gauge had been in continuous use since early 1880 and maintenance was proving difficult as the parts were much worn. With few exceptions, the monthly totals from all gauges appear in the published *Radcliffe Observations* and since 1935 in the *Monthly Weather Report*. Various authors have quoted the Radcliffe rainfall record and produced summaries and tabulations which do not always agree with the figures on which they are based. The basic observations seem to have been made with commendable, indeed meticulous, care and devotion; queries which concern tabulations can often be resolved by reference to the original records. The homogeneous record produced by Knox-Shaw and Balk (1932) takes account of only three of the rain-gauges. It is discussed in more detail in section 5.

3. THE INDIVIDUAL GAUGES, 1815–1880

Hornsby's original rain-gauge which was in use in 1815 was of 12 inches diameter with a conical funnel 10½ inches deep (Rigaud, 1835) and was sited on the roof of the east wing of the Observatory. Plate I shows the east and central part of the building from the north, with a later extension of the Radcliffe Infirmary in the background. Rigaud (1835) and the Observatory year-books state that a pipe led from the rain-gauge down into the north-west corner of the quadrant room, where the rain was collected and measured. Subsequent alteration and interior decoration in the building have removed all traces of this arrangement, but the exact site of the rain-gauge on the roof was described by Rigaud (1834). This confirms a note in the Meteorological Office records which states that the gauge was about 60 ft from the tower. Its location is indicated at point A on the plan in Figure 1. The tower is over 112 ft high and this site, near a large obstruction, seems a curious choice in view of the insistence by the Secretary of the Royal Society, Dr Jurin (1723) that the exposure of a rain-gauge should be open in all directions. However, this site was probably chosen by Hornsby while the Observatory was being built (progress on the completion of the tower was delayed until 1794 for financial reasons) and it was probably better exposed than the sites of roof gauges previously used by Hornsby in Oxford (Craddock and Craddock, loc. cit.). Hornsby's successor, Professor S. P. Rigaud (1834) discusses this question of the possible sheltering effect of the tower and, by somewhat doubtful arguments and mathematical calculations, comes to the conclusion that 'from these data it may well be doubted whether the rising building diminishes at all the rain which falls into the funnel'. It seems that by 1850 doubts had arisen about the adequacy of the east wing exposure, because in that year a gauge of 10 in. diameter, with rim 11 in. above the ground, was installed on the south lawn near point B. Nevertheless in 1851 the Observer reported that, in his opinion, the loss of catch by the roof gauge due to the presence of the tower was only slight (*Radcliffe Observations* 1851). In 1862 the roof gauge was raised two feet by placing it on, instead of behind, the parapet 'to improve the exposure'. For the same reason the ground gauge was moved in May 1862 from point B to an area near point C on the north lawn, which, apart from an interlude from 1935 to 1939, has been used for rain-gauges ever since. This western part of the north lawn, with its surroundings, is shown in Plate II. In 1862 a third gauge was installed with rim 22 ft above the ground on a lattice above the roof of a disused anemograph hut. This hut is stated in the 1862 *Yearbook* to have been on the north lawn 'at a considerable distance from the Observatory' and was no longer required when the anemograph was installed on top of the tower. A fourth rain-gauge, with rim 112 ft above the ground, was also installed on the tower in 1862. These gauges were of 10 in. diameter, with pipes leading down to collecting vessels. In 1868 when the anemograph hut was demolished, the 22 ft gauge, with its lattice, was moved to a position above the north-west corner of the wall surrounding the kitchen garden of the observer's house (Point D on Figure 1). This ancient wall still exists, although the kitchen garden does not, and can be seen in Plate III, which is taken looking north-eastwards from the balcony platform of the Observatory where the telescopes were wheeled out for observation. In the kitchen garden site the 22 ft rain-gauge was higher than any object nearby, and the exposure was 'free in all directions'. This statement is repeated at intervals of several years in the annual editions of *Radcliffe Observations* and Plate III shows that it is true today. In 1877 a new

Glaisher gauge of 8 in. diameter, with rim 11 in. above the ground, was installed near point C and about five feet from the old 10 in. ground gauge. Comparisons were maintained daily until the end of 1880 when the old 10 in. gauge was removed. At the same time the old east wing roof gauge was taken out of use and a new Beckley self-recording gauge was installed near point C. This had a funnel of 11·3 in. diameter with rim 28 in. above the ground, and generally caught more than the Glaisher gauge next to it. In 1887 the rim of the 8 in. Glaisher gauge was raised from 11 in. to 20 in. above the ground. This may have been on Meteorological Office advice or to make a better comparison with the Beckley gauge.

4. The rain-gauges after 1880

From 1880 until 1883 the published observations give totals for the Beckley gauge and after 1883 for the 8 in. Glaisher gauge, together with the totals of the Beckley self-recording gauge and the kitchen garden and tower gauges. Towards the end of 1907 it was discovered that the kitchen garden gauge had sprung a leak near the rim and the decision was taken not to repair it 'as 40 years of daily records should be enough for all purposes'. The year 1908 was the last one in which the tower gauge was maintained, but the Beckley gauge continued in use until 1963 when it was replaced by a Dines tilting-siphon recording gauge. The daily charts for the Beckley gauge were analysed and tabulated up to 1953. Until 1902 this gauge appears to have read rather higher than the 8 in. Glaisher gauge and there are frequent references in the pocket books to minor adjustments to the mechanism. From 1906 onwards the Beckley gauge appears to have functioned much better and to have caught about one per cent more than the Glaisher. After 1920 the modern practice was adopted of adjusting the hourly and daily readings of the self-recording gauge to agree with those of the 8 in. Glaisher gauge. When Dr Knox-Shaw became Radcliffe Observer in 1924 he decided that the rainfall record should be reduced to a common standard, that of the 8 in. Glaisher gauge; and, as there was only a three-year overlap from 1877 to 1880 between the record of the Glaisher gauge and that of the old east wing roof gauge, the latter gauge was revived from 1923 to 1930 and read daily. The daily totals of the roof gauge during this period have never been published but survive in the observer's pocket books. Mr J. G. Balk used them to calculate monthly conversion factors to bring the totals from the roof gauge between 1815 and 1862 to the standards of the Glaisher gauge.

In 1935 the Radcliffe Observatory moved to Pretoria but, after some uncertainty, it was agreed that the responsibility for continuing the meteorological record should be assumed by the Professor of Geography (School of Geography MSS). A stipend was provided to enable Mr Balk, who had joined the Observatory in 1903 as a computer, to continue as Radcliffe Meterological Observer until his retirement in 1953. Discussion with those who remember him and obituaries published in Oxford newspapers in 1955 show him to have been something of a local character. As a survivor of the old regime he may have been somewhat set in his ways, but the numerous records and notes which survive in his hand show him to have been a most careful and dedicated worker. Since 1935 responsibility for the maintenance of the Radcliffe Meteorological Station, and for the appointment of an observer, has remained that of the Professor and staff of the University School of Geography. The Observatory building and the observer's house were taken over by the newly founded Nuffield Institute for Medical Research in

1935, and more recently by the offices of the University Medical School. The building will shortly be occupied by Green College, a new foundation for clinical medical students. Since 1935 the area of the hospital on the south side of the old observatory has expanded enormously. One consequence of the removal of the astronomical observatory in 1935 was a decision to move the rain-gauges from point C to a point on the south lawn near E. This meteorologically surprising move was a result of *force majeure* since the garden on the north side was to become private. However, as a fortunate result of wartime emergency construction in 1939, it was necessary to move the gauges back to near point C on the north lawn, where they have remained ever since. The importance of this site for the continuation of meteorological records has recently been recognized by a University decree.

Today, although the buildings and the north lawn have changed hardly at all since Hornsby's day, the south lawn and surrounding wall have disappeared beneath Infirmary extensions and a car park. In 1963 the 8 in. Glaisher gauge was replaced by a modern 5 in. Meteorological Office pattern gauge at the same time as the Beckley gauge was replaced by the Dines recording gauge. This was done on instructions from the Meteorological Office which had supplied both Beckley and Dines gauges. Unfortunately it was not considered necessary, by those responsible for this change, to maintain an overlap between the 8 in. and 5 in. gauges, presumably because it was assumed that the results would be so similar as to make this unnecessary.

5. The Knox-Shaw and Balk reductions

The reduction of the rainfall records to provide monthly totals since 1815 was carried out by Mr Balk on the instructions of Dr Knox-Shaw. He must have relied on substantially the same documents which are preserved today. Mr Balk, no doubt as a result of his training as an astronomical computer, showed an attention to detail which, however necessary in astronomy, is rare in meteorology. The principles behind the reductions are succinctly described by Knox-Shaw and Balk (1932). They elected to use records from only three of the rain-gauges which had been in use since 1815, namely those of the east wing roof gauge from 1815 to 1861, those of the 8 in. Glaisher gauge from 1877 until 1930 and those of the 10 in. gauge on the north lawn for the years in between. Two major problems arise in any attempt to render homogeneous the records of these different gauges. Firstly, during the period from 1816 to 1833 when rainfall was not recorded every day, the totals for the east wing roof gauge have to be apportioned between the months. This involves a certain element of intuitive guesswork and a reliance on the brief remarks in the observer's weather diary. To a lesser extent a similar problem arises with the fuller and more reliable daily records later in the 19th century because the time of daily observation was not always the same. Thus, for a period when rainfall was measured from noon to noon, it was often necessary to make a small adjustment to the monthly totals. Inspection of the corrections made in the original pocket books and manuscript records by Mr Balk, and in some cases by his predecessors, suggests that this problem has been treated as carefully and accurately as the surviving evidence will permit.

Once the daily totals have been adjusted in this way to give a reliable monthly total, the readings of the various rain-gauges in use at different periods have to be brought to the standard of the 8 in. Glaisher gauge by the application of conversion factors found from an evaluation of overlapping records. The various conversion factors found by Knox-Shaw and Balk and used in their homogenization have been recalculated and checked and the conclusion reached that in this case too the calculations and conclusions are as reliable and accurate as the evidence permits. A full treatment of these conversion factors would be tedious. However, some examples can be given to illustrate the method and reliability. Knox-Shaw and Balk state that the readings of the roof gauge on the east wing have to be multiplied by a factor, 'which in the mean is 1·130' to reduce them to the standard of the 8 in. gauge on the north lawn. This was deduced from the readings of the re-installed roof gauge between 1923 and 1930. This figure was checked and calculated again from the entries in the observer's pocket books and found to be correct to the second decimal place. They found that 'the factor varied with the month, rather than with the monthly total of rain' and quote a different factor for each month. Our calculation of the monthly factors did not produce quite such a close agreement. In winter months, with little rain and considerable snow, Knox-Shaw and Balk appear to have made some allowance for a greater difference between the two gauges. Doubts, which we both had, whether the comparison of the roof gauge with the ground gauge during the period 1923–30, in the middle of a period when the westerly weather type was particularly frequent, would necessarily be applicable to a period in the mid-19th century, caused us to calculate conversion factors for the periods 1851–61 and 1862–79, when the 10 in. ground gauge was sited at point B and point C respectively. It seems strange that Knox-Shaw and Balk did not use data available for these periods—or if they did, they made no reference to having done so. To our surprise these comparisons vindicated the Knox-Shaw and Balk conversion factor. A comparison of the annual totals of the east wing roof gauge with the 10 inch ground gauge on the south lawn from 1851 to 1861 gave a mean conversion factor for the former of 1·133 while a comparison of the roof gauge and the 10 in. gauge on the north lawn between 1862 and 1879 gave a mean conversion factor of 1·153. In each case the conversion factor would apply to the reading of an 8 in. gauge on the north lawn. To determine these factors it was necessary to make use of the comparison between the Glaisher gauge and the 10 in. gauge on the north lawn between 1877 and 1880 as well as the overlap between the records of the roof gauge and of the 10 in. ground gauge situated successively on the south and north lawns between 1850 and 1880. A direct comparison was possible over the short period from 1878 to 1879 between the east wing roof gauge and the 8 in. Glaisher gauge; this gave a conversion factor for the roof gauge of 1·121. Closer agreement between the Knox-Shaw and Balk mean annual conversion factor of 1·130 and that calculated for other periods can hardly be expected in view of the known limits of accuracy of standard rain-gauges. An examination of the monthly and annual values of the east wing roof gauge and the various ground gauges in use during all the periods described above shows that there is quite a significant variation about this mean from month to month and even from year to year. The annual correction factor over 37 years had a standard deviation of 0·045. This is to be expected since the frequency of particular wind directions and the predominance of particular weather types are likely to affect the proportion of precipitation caught by the elevated gauge partly sheltered by the tower as compared with one well exposed on the ground. The total amount of precipitation during a month, its intensity, and particularly the amount falling in the form of snow are likely to produce further variations in the difference. One must conclude that, in view of the inherent complexity of the problem, the Knox-Shaw and Balk reductions are probably the best that can be made for the period when the only Oxford rainfall data are those from the east wing roof gauge. However, the need for the application of substantial correction factors to all monthly totals before 1851, factors which are averaged over months or years, introduces an additional source of error in the homogeneous values, compared with corresponding totals for later years. The importance of these errors depends on the manner in which the monthly totals are used, and is discussed further in section 8. There is one further and, as far as the winter months are concerned, probably more serious reservation about the early rainfall figures. From the data it is not clear when snowfall was treated as precipitation and included in the rainfall totals. Certainly on many occasions before 1851 there are references to snow in the observer's pocket books and the manuscript record with no obvious subsequent rainfall entry to suggest that this was measured after it had been allowed to melt. If the observers did not consider that snow should be measured and included as rainfall, and there is some evidence to suggest that this was the case, then in some years at least the winter precipitation values will be significantly reduced. However, the same attitude may have been taken by contemporary observers elsewhere and as A. Bleasdale (personal communication) has pointed out: 'early practices with regard to snow were chaotic and provided G. J. Symons with one of his fields for recommendations and standardization'. The relative dryness of the winters in the early 19th century noted by Smith (1974), and the change of rainfall regime since, may therefore be more apparent than real if in some years a significant proportion of the winter precipitation was unrecorded.

6. The Botanical Gardens (Magdalen) rainfall record

There is a complete daily rainfall record from a ground gauge in the Botanical Gardens at Oxford from 1870 to 1953, and a similar record from a roof gauge, at a height of 34 ft, from 1882 until January 1936. After 1 August 1923, the roof gauge was only read monthly on the first day of each month. Like the early Radcliffe records, monthly values of these gauges are included in the 10-year books in the Meteorological Office archives, and the ground gauge data were published in *British Rainfall;* they have thus been used and quoted by a number of researchers. The early history of this rainfall record is described by Gunther (1904) and there are brief notes which do not add very much to this information preserved with the original manuscript records from 1867 to 1935 in the library of Magdalen College. These records are neat and well maintained and to a large extent duplicate the Radcliffe meteorological observations, since they include wet- and dry-bulb and maximum and minimum temperatures, wind direction and force and the height of the River Cherwell which flows past the site. The observations, like the science laboratories where they were taken, owe their initiation to Dr Daubeny, a Fellow of Magdalen College. In the present century the buildings became part of the University science laboratories and responsibility for the meteorological observations passed to the Curators of the Botanical Gardens, although the record continued to be described as 'Oxford, Magdalen College' which lies just across High Street to the north. Reports to the Meteorological Office by Dr R. T. Gunther in 1907 and the report of a visit by Mr H. E. Carter of the Meteorological Office in 1948 confirm that the ground gauge in use at these times was the same, and it appears to have been the one originally installed in 1870. It was described as a five inch circular gauge with a shallow funnel made by Casella. It was mounted in a concrete block. 'A heavy metal collar with a locking arrangement fits around the top of the gauge almost flush with the rim.' Carter (1948) also noted: 'there could be insplashing in heavy rain from the metal collar and concrete block but this might be offset by outsplashing from the shallow funnel'. Little is known about the roof gauge other than the note by Gunther quoted above which states that the gauge was of five inches diameter on the roof of the Laboratory. Two gauges had been mounted on the College roof between 1867 and 1882 at heights of 57 ft and 64 ft but it was thought that the exposures were poor owing to shelter from chimney stacks. These gauges were only read intermittently. Preserved in the College library are some earlier but intermittent rainfall records from January 1867 until the end of 1869. The observer's manuscript books indicate that from 1870 until the end of 1875 the rim of the ground gauge was 7 in. above the ground but, apparently on the advice of G. J. Symons of the British Rainfall Organization, it was then raised to 12 in. above the ground. All the meteorological observations at the Botanical Gardens were discontinued in 1953 as a result of vandalism; the site was at a spot much frequented by the public. After 1935 the record was maintained by technicians from the University chemistry laboratories and in spite of a search the manuscript records for this period have not been found. The figures used and quoted from 1936 to 1953 have been supplied from the Meteorological Office archives.

The Magdalen rainfall record has been used in the subsequent discussion in this paper to help resolve some problems which arose when comparing the various gauges in use at the Radcliffe Observatory from 1868 to 1907. The Botanical Gardens are situated 1550 metres south-east of the Radcliffe Observatory but at a slightly lower altitude above mean sea level, 58 m as compared with 63 m. Both are sufficiently close to the centre of Oxford to have been in effect urban sites throughout the period of record although, as noted earlier, building on the south side of the Radcliffe Observatory this century has significantly reduced the amount of open space in the immediate vicinity.

7. Comparisons between rain-gauges at the Radcliffe Observatory and the Botanical Gardens

From 1868 until 1907 four rain-gauges were continuously in use at the Radcliffe Observatory although the sites and the individual gauges were not always the same. During this time the 8 in. Glaisher ground gauge, adopted as the standard by Knox-Shaw and Balk, was introduced and it was with a view to investigating the validity of their reduction that comparisons between the annual totals of the various gauges were made. The fact that for the whole of this period two of the gauges were elevated well above ground level in unorthodox exposures adds further interest to the comparison. The comparisons can be summarized in Table I and Figures 2 and 3. Table I lists the annual falls recorded by certain rain-gauges as a percentage of the mean for the period. The gauges are: (a) the Radcliffe ground level gauge (the 8 in. Glaisher reading after 1879, and the 10 in. gauge reading before that, corrected by the factor used by Knox-Shaw and Balk). The figures are, therefore, those of the homogeneous record of these two workers; (b) the reading of the Radcliffe kitchen garden gauge at an elevation of 22 ft; (c) that of the Radcliffe tower gauge at an elevation of 112 ft; (d) the record of the

'Magdalen' ground gauge, and (e) that of the 'Magdalen' roof gauge at an elevation of 34 ft. Figure 2 is a graph showing the catches of the Radcliffe elevated gauges as a percentage of that of the Radcliffe ground gauge.

TABLE I—ANNUAL PERCENTAGE OF THE LONG-PERIOD MEAN FOR FIVE OXFORD RAINFALL RECORDS

	(a)	(b)	(c)	(d)	(e)
1870	69·4	68·5	59·9	66·1	
1	83·6	84·3	80·2	85·4	
2	117·9	116·9	102·1	119·5	
3	92·7	87·8	80·0	92·5	
4	84·7	83·4	72·4	86·3	
5	130·9	128·0	117·1	133·7	
6	128·3	127·4	122·4	127·9	
7	119·2	117·1	115·6	118·4	
8	106·7	106·9	118·3	113·7	
9	124·3	124·4	109·0	128·8	
1880	124·8	—*	137·6	127·3	
1	105·2	—*	100·6	102·3	
2	127·1	126·2	126·7	134·2	134·4
3	107·5	109·1	112·7	117·6	117·8
4	76·3	76·6	73·9	80·3	74·7
5	104·0	101·0	102·9	107·1	112·8
6	128·9	126·2	132·7	132·4	134·5
7	77·1	82·5	72·3	77·4	79·2
8	110·2	111·2	106·6	112·9	113·7
9	95·0	94·7	95·4	91·7	99·3
1890	71·9	71·9	69·4	70·2	74·8
1	111·7	111·7	110·1	109·6	117·3
2	82·8	85·1	86·6	77·2	80·1
3	71·3	73·1	69·9	68·3	70·9
4	115·2	119·5	123·8	115·0	124·3
5	91·2	93·7	93·5	90·2	94·8
6	95·4	98·5	99·9	90·8	96·6
7	106·4	110·3	113·5	101·1	107·2
8	77·6	81·7	79·4	75·7	80·6
9	84·9	89·3	89·1	84·3	87·1
1900	95·3	99·8	94·2	96·2	101·0
1	89·9	94·7	96·1	88·3	91·4
2	67·3	72·7	71·3	70·1	71·5
3	145·1	149·3	159·2	144·9	155·2
4	91·5	93·2	100·7	87·3	91·7
5	84·5	82·7	88·6	78·6	81·8
6	96·9	92·8	99·1	91·7	95·7
7	108·1	108·3	118·1	105·2	111·3
Mean annual fall over above period (inches)					
	24·77	24·22	16·95	24·25	20·57

(a) Radcliffe ground gauge (Knox-Shaw & Balk)
(b) Radcliffe 22 ft kitchen garden gauge
(c) Radcliffe 112 ft tower gauge
(d) Magdalen ground gauge
(e) Magdalen roof gauge at 34 ft

* Data unreliable owing to leaky gauge.

The graphs and the table show year-to-year fluctuations as is to be expected when the intensity of rain and the frequency of different weather types are as variable as they are in Britain. The first impression from Figure 2 is that the tower gauge at the Radcliffe Observatory was less efficient in the 1870s than subsequently. This could be explained by some undocumented changes in its exposure consequent upon the mounting of a new anemograph on the tower in 1880. A second and more disturbing conclusion is that both the elevated gauges

FIGURE 2—ANNUAL RAINFALL RECORDED BY THE ELEVATED GAUGES AT THE RADCLIFFE OBSERVATORY AS PERCENTAGES OF THE ANNUAL FALLS RECORDED BY THE GROUND GAUGE, 1868–1908

became relatively more efficient than the ground gauge from 1892 onwards. The kitchen garden gauge actually caught more than the ground gauge between 1892 and 1903 after which its readings fell back to levels similar to those registered before 1890. It was at first thought that this might have been caused by increasing shelter of the ground gauge from growing trees in the garden. A search of all available contemporary pictures, photographs and records of the garden, which was always kept well tended and ornate, failed to reveal any positive evidence of this although the possibility cannot be rejected entirely. Another possible explanation is that the growth of Oxford in the late 19th century produced changes in the wind profile around the Observatory which may have increased the relative catch of the two elevated gauges. Other possible explanations have been investigated: the rim of the Glaisher gauge was raised from 11 in. above the ground to 20 inches in 1887 and thereafter remained at this level. On more than one occasion it was noted in the observer's pocket books that the tubes leading from the high-level gauges to their collecting vessels had become blocked and had had to be cleaned out; this might have been expected to reduce their catch rather than to increase it, as would the effect of snow being blown out of the high-level gauges. It was noted in the pocket book for 1905 that the glass measure for the 8 in. Glaisher gauge was broken on 15 August and replaced on 18 August by a new measure supplied by the Meteorological Office. The broken measure had, it was noted, been in use for 25 years so that wrong calibration of a measuring cylinder could not have explained a decline in the catch of the ground gauge

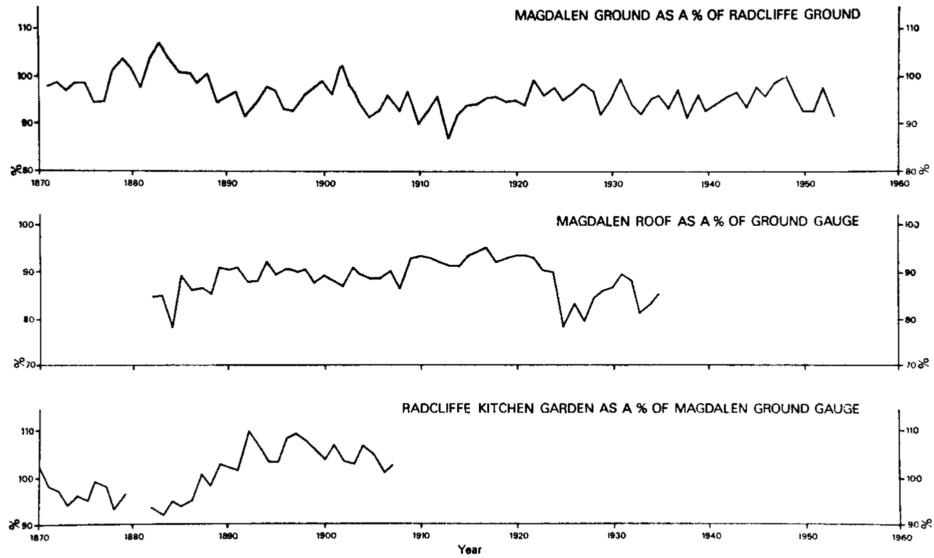

FIGURE 3—ANNUAL RAINFALL RECORDED BY THE 'MAGDALEN' GROUND GAUGE COMPARED WITH THE FALLS RECORDED BY THREE OTHER GAUGES, FOR VARIOUS PERIODS BETWEEN 1870 AND 1953

around 1892. However, it appears that the measuring cylinder used for the high-level gauges was made or calibrated by the Observatory so that any change of measuring vessel during this period might have affected the readings of the upper gauges.

The apparent discrepancy between the ground and high-level gauges has been investigated at some length since it was not referred to by Knox-Shaw and Balk and they may not have noticed it. If there was a decline in the efficiency of the ground-level gauge at this time it would have seriously affected the validity of their reduction of earlier readings to the standard of the 8 in. Glaisher gauge. In order to try to resolve this problem the manuscript records of the two 'Magdalen' gauges were checked and then compared with the Radcliffe rainfall records. The Magdalen ground gauge is probably less reliable than the Radcliffe Glaisher gauge and it was not so well exposed. Figure 3 shows graphs of the annual totals of the Magdalen ground gauge as a percentage of the Radcliffe ground gauge, of the Radcliffe kitchen garden gauge and of the Magdalen roof gauge. This comparison seems to contradict the evidence from Figure 2 that during the latter part of the 19th century and until 1903 the Radcliffe ground gauge was becoming less efficient. In spite of a greater year-to-year variation between the ground gauges at the two different sites, the Magdalen annual rainfall totals are about 95 per cent of those at the Radcliffe Observatory with the exception of a few years around 1880. The period from 1875 to 1885 was one of notably wet summers when rainfall may have been particulaly intense, and this might be an explanation; alternatively the Magdalen gauge may have been defective for this short period. The mean difference between the two gauges is consistent with known and explicable rainfall gradients in Oxford consequent upon the local relief. The comparison between the Magdalen ground gauge and the Radcliffe kitchen garden gauge between 1892 and 1893 suggests that it was this latter gauge that was inconsistent with the record of the ground-level gauges at both sites. The comparison between the Magdalen ground and roof gauges over the period 1882–1924 shows no trend in the difference between the two gauges, but the annual totals for the roof gauge were reduced after 1923 when the gauge was read only once a month instead of daily as before. Presumably this was a consequence of evaporation loss or of the monthly accumulation of small daily totals when the gauge was read daily.

The evidence of Figures 2 and 3 together with the annual percentage figures in Table I seems to point to the conclusion that for a variety of reasons the records of the elevated gauges at the Radcliffe Observatory are not so reliable as that of the ground gauge. This 8 in. Glaisher gauge, together with the Beckley self-recording gauge that stood alongside it, became the standard rainfall record of the Observatory after 1880. The readings of the Glaisher gauge were reported to the Meteorological Office and to the British Rainfall Organization and the Observatory was in regular communication with both organizations. During the period from 1880 to 1914 the Radcliffe was one of the most important meteorological observatories in the country and its observations were included in the *Daily Weather Report*. The Observatory must have been visited and inspected by professional meteorologists at regular intervals, although no correspondence to confirm this survives at Oxford. It seems improbable that the Meteorological Office would have accepted readings from a defective or badly exposed rain-gauge at this station.

On balance it seems more likely that the elevated gauges were imperfect and their records less carefully scrutinized for error and inconsistencies. It is known from a note in the published *Observations*, and from manuscript notes in the pocket books, that in 1880, 1881 and 1907 leaks were discovered near the rim of the kitchen garden gauge and that these rendered the readings for 1880, 1881 and 1907 too great. On the first two occasions the leak was repaired and it is possible that on the third occasion it had existed for some years before it was detected and that it had become progressively worse. These comparisons may be summed up by saying that while there are disrepancies between the records which show that some of the records must have been defective in some years, the agreement after 1889 between the ground gauges at the Radcliffe Observatory and the Botanical Gardens leads us to prefer their testimony, rather than that of the elevated gauges. Moreover, we feel that while the reduction by Knox-Shaw and Balk includes many details which would probably be omitted if the work were done today, these are inessential rather than objectionable. There is scope in the volume of records for a much fuller investigation, but unless this can be carried out, we are inclined to accept the Knox-Shaw and Balk figures as the best available.

8. Discussion

This paper is concerned above all to set out the facts about one of the longest and best-kept collections of meteorological data that exists for any place in Great Britain. Possible applications are explored only lightly, but the following are some of the main prospects.

(1) Although the Radcliffe rainfall records discussed here start in the year 1815, the paper by Craddock, J. M. and Craddock, E. (1977) provides an

extension back to 1767 with the annual totals from 1776 to 1804 to the same rain-gauge and site as was used later from 1815 onwards. The Radcliffe rainfall records fall into two parts: the first, that of the east wing roof gauge, started in 1776 and continued, with some unfortunate breaks, until 1880; the second is of ground gauges, and started in 1850 and is continuing still. During these 200 years, the immediate surroundings of the gauges have changed little, and changes in the surrounding terrain are less in extent and better documented than they are for most town sites. Hence the Radcliffe records are unusually suitable for investigating changes on the climatic time-scale.

(2) The records from 1868 to 1907 provide evidence on the problem of correcting a record for the elevation of the gauge, which arises with many early rainfall records. While the problem has been known for 200 years, most investigations have covered a few years, at most, and produce discordant results due, probably, to differences in the surrounding terrain. Table I shows that the high-level gauges agree very well with the more conventional exposures in showing the wettest and driest years, and that the agreement could be improved still further if the departures for the high-level gauges were scaled down somewhat. This subject deserves examination with the inclusion of similar comparative records made elsewhere.

(3) Investigations based on daily rainfall and temperatures etc. can be made using a range of basic data which does not exist in most places.

In conclusion, we may remark that the fact that this paper is concerned so much with the defects of rain-gauges may give the impression that the Radcliffe observations are slipshod and unreliable. The truth is exactly the opposite, because it is the number of carefully kept and comparable observations which has enabled us to piece the story together, and to bring to light minor discrepancies which in most circumstances would be incapable of being detected. These observations can help to elucidate unanswered questions of the British rainfall regime of the last two centuries, and could provide the material for several Ph.D. theses, besides the work on the above topics which the authors hope to undertake. It must be emphasized that nearly all British rainfall records for years before 1800 were made with elevated rain-gauges, and that the correction of such records to the standards of a 1 ft gauge is an essential part of any serious attempt to probe the rainfall regimes of the past.

9. Acknowledgements

The authors wish to acknowledge help in finding relevant information from the following: the staff of the Rainfall Quality Control Unit in the Meteorological Office; Miss Elspeth Buxton, Librarian of the School of Geography, University of Oxford; Mr G. L. Harriss, Librarian, Magdalen College; and the staff of the Bodleian Library, Oxford.

Valuable assistance in checking manuscript records and in calculation was given by Mr J. Samson, Radcliffe Meteorological Observer, 1975–76, and Mr T. G. Smith.

References

CARTER, H. E. 1948 Rainfall, Magdalen College, Oxford. (Memorandum in the archives of Meteorological Office, Met O 3b (report on a short visit to the station on 19 May 1948).)

CRADDOCK, J. M. and CRADDOCK, EVELINE	1977	Rainfall at Oxford from 1767 to 1814, estimated from the records of Dr Thomas Hornsby and others. *Met Mag*, **107**, pp. 361–372.
GUNTHER, R. T.	1904	A history of the Daubeny Laboratory at Magdalen College, Oxford, pp. 31–47.
	1923	*Early science in Oxford*, Vol. 1, p. 323. (Private subscribers only, reprinted in *Oxford Historical Society Publications*, Vol. 77).
JURIN, J.	1723	Invitation to make weather observations according to a common plan. *Philos Trans R Soc*, **33**, pp. 422–427.
KNOX-SHAW, H. and BALK, J. G.	1932	Appendix 'A' to *Results of meteorological observations made at the Radcliffe Observatory, Oxford in the five years* 1926–30, p. 95.
RADCLIFFE OBSERVATIONS	1853–1937	*Astronomical observations made at the Radcliffe Observatory, Oxford*, Vols 7–13 (for the years 1847–52).
		Astronomical and meteorological observations made at the Radcliffe Observatory, Oxford, Vols 14–47 (for the years 1853–91).
		Results of the meteorological observations made at the Radcliffe Observatory, Oxford, Vols 37, 48–52, 54–56 (for the years 1876–79 and 1892–1935).
RIGAUD, S. P.	*ca* 1834	Bodleian Library, Oxford. MSS Rigaud 49, Folio 140–74.
	1835	The proportional quantities of rain at Oxford at different seasons. *Trans Ashmolean Soc, Oxford*, Vol. 1, (read 13 March 1835).
SCHOOL OF GEOGRAPHY, UNIVERSITY OF OXFORD	—	Correspondence concerning the possible cessation of the meteorological observations at the Radcliffe Observatory site, 1931 onwards.
SMITH, C. G.	1969	The Radcliffe Meteorological Station. *Weather*, **23**, pp. 362–367.
	1974	Monthly, seasonal and annual fluctuations of rainfall at Oxford since 1815. *Weather*, **29**, pp. 1–16.
	1975	The character of the summers at Oxford since 1815, in *Oxford and its region* (Smith, C. G. and Scargill, D. I., editors), pp. 14–28.

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COMPUTER PROCESSING OF SATELLITE IMAGE DATA

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SUMMARY

The automatic processing by a small computer of visible and infra-red image data from meteorological satellites is described. The process includes digitization, projection, and output in a variety of forms. Output via a facsimile recorder has been in experimental operational use since November 1976. The technique is compared with the current operational procedure.

INTRODUCTION

This paper describes the automatic processing of satellite image data (visible and infra-red) from NOAA 5 and Meteosat in the PDP 11/40 computer laboratory operated by the Systems Development Branch (Met 0 22) of the Meteorological Office. Similar techniques have been developed by other meteorological services: those described here are adapted to the needs of the United Kingdom service. In the case of NOAA 5 data the resulting pictorial output is already in use in the Central Forecasting Office (CFO), supplementing the directly received pictures, as viewed from space, which have been generally available for some years.

THE CURRENT OPERATIONAL PROCEDURE

In the current procedure operated in CFO, a forecaster specialized in the analysis of satellite pictures takes the direct earth-views, examples of which are shown in Plate IV, and adds a latitude/longitude grid by means of an overlay chosen from a standard set. This grid is located relative to two timing marks shown in Plate IV as lines of alternate black and white which are added automatically at the satellite ground receiving station at RAE, Lasham in Hampshire. Sometimes the marks, which are actual scan lines for the presumed times at which the satellite crosses latitudes 65 and 40 degrees north, are several seconds out, or missing altogether, which can cause problems in locating the grid. The next step is the construction of a composite nephanalysis which incorporates eye-interpretation of cloud patterns from successive (visible and infra-red) pictures and involves a rather awkward transformation from the earth-views to a 1:20 million polar stereographic map projection. Both the original pictures and the nephanalyses are used by forecasters in CFO, although only the latter can be superimposed on their normal working charts. The former contain details which cannot be represented on a nephanalysis and are valued tools in spite of their distorted perspective. Whereas nephanalyses are sent by facsimile broadcast to all official outstations, only selected stations receive the pictures themselves.

THE COMPUTER AND THE ASSOCIATED PROCEDURE

The PDP 11/40 is a small but powerful computer of the type often referred to as a 'mini-computer'. It has a wide range of peripheral devices attached to it, those of significance in the present context being shown in Figure 1. Its main use is for

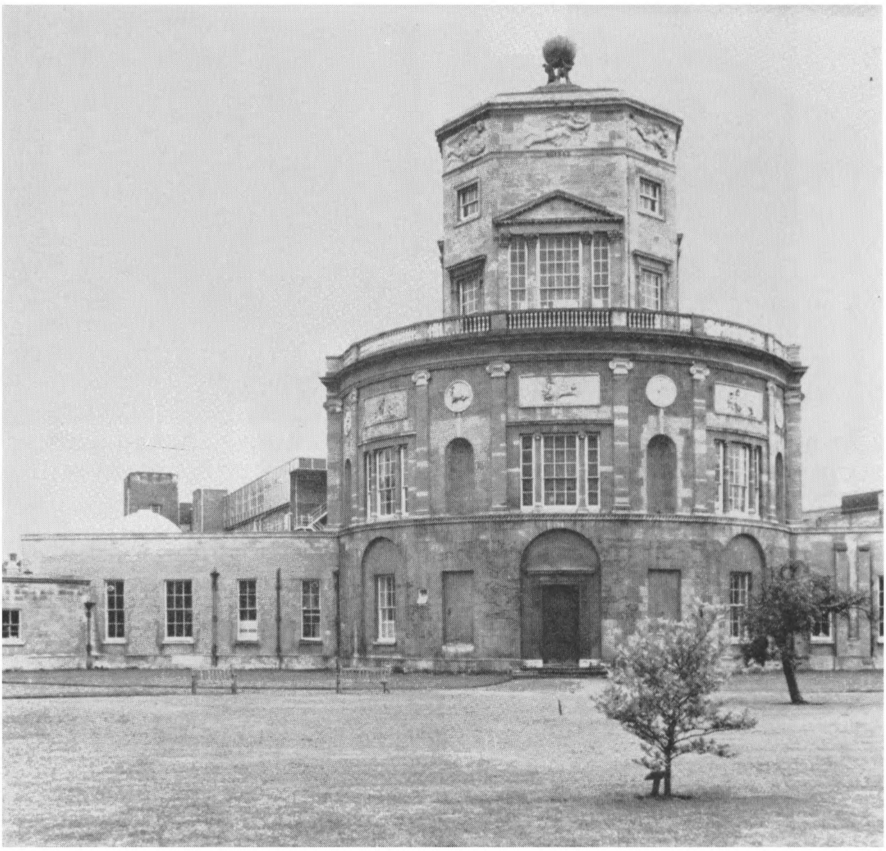

PLATE I—THE RADCLIFFE OBSERVATORY IN OXFORD IN 1978, LOOKING SOUTH AND SHOWING THE EAST WING, THE BALCONY AND THE TOWER

The design of the tower of the observatory is roughly based on the Horologium of Andronicus of Cyrrhus at Athens, built in the first century B.C. and usually called the 'Tower of the Winds'. The Horologium still stands in a good state of preservation near the Roman agora at the foot of the hill of the Acropolis, and a drawing of it is used as the emblem of the Royal Meteorological Society. In ancient times it had a sundial, a water clock (for cloudy days) and a wind vane in the form of a Triton. (See Plates II and III between p. 300 and p. 301 in the *Meteorological Magazine* for October 1970.) (See page 260.)

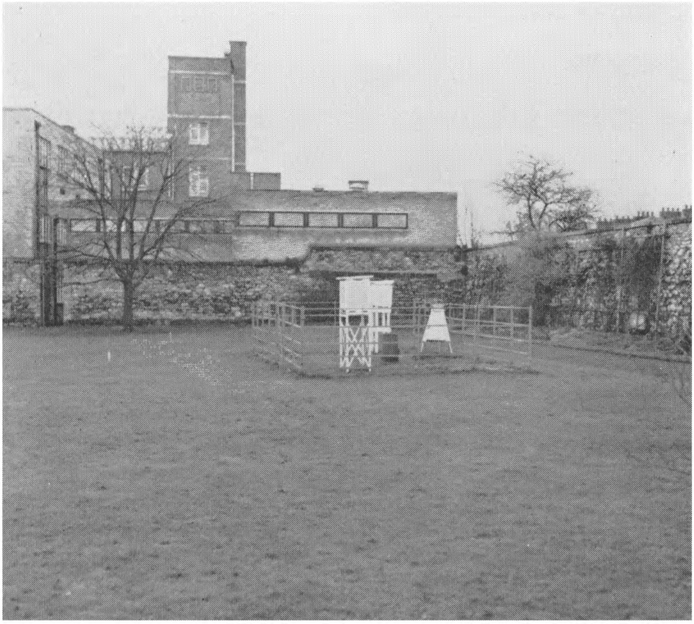

PLATE II—THE NORTH LAWN OF THE RADCLIFFE OBSERVATORY, OXFORD, LOOKING SOUTH-WEST TO SHOW THE RAIN-GAUGE AND THE NORTH-WEST BOUNDARY WALL

(See page 260)

PLATE III—LOOKING NORTH-EAST FROM THE BALCONY OF THE RADCLIFFE OBSERVATORY, OXFORD, TO SHOW THE KITCHEN GARDEN WALL AND THE SURROUNDINGS

(See page 260)

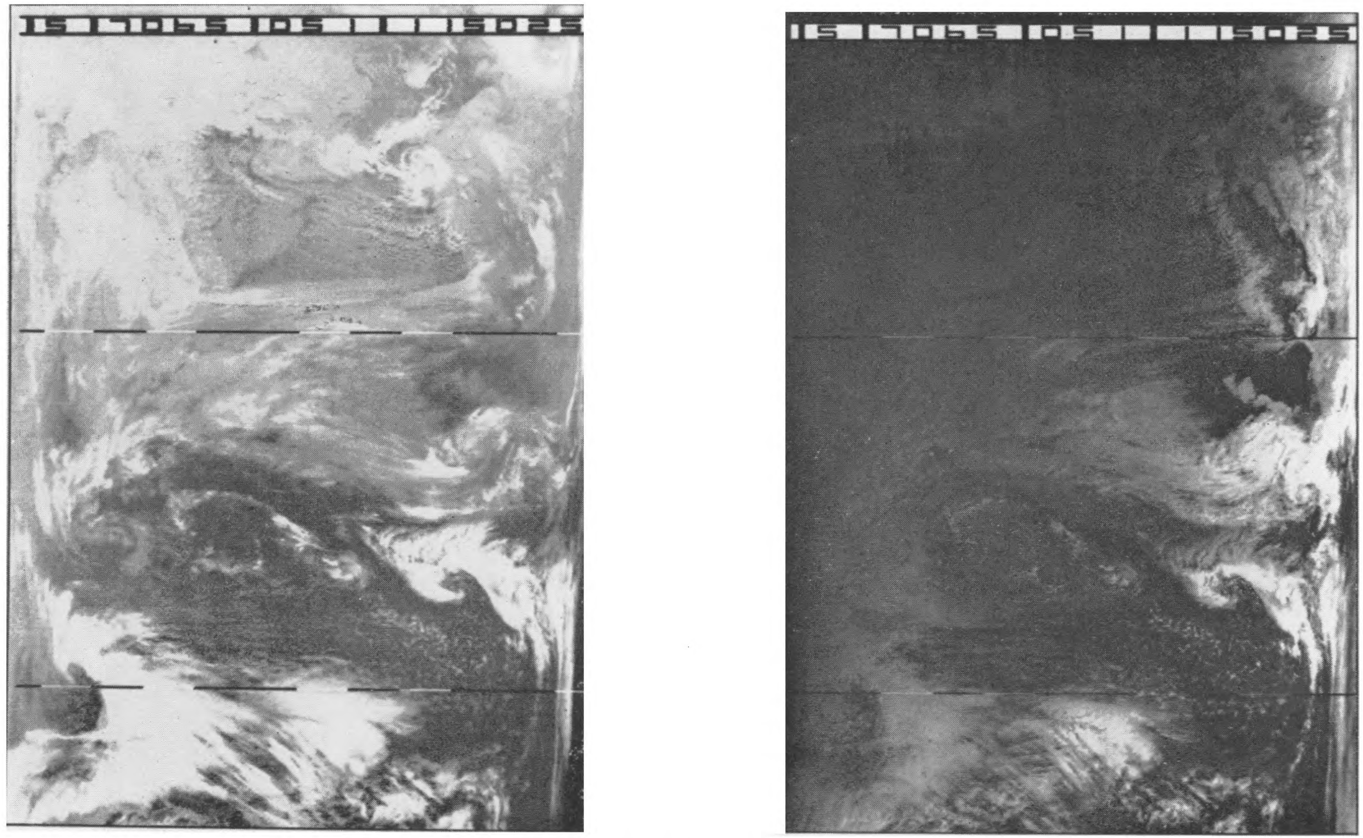

PLATE IV—SINGLE ORBIT BEFORE PROJECTION AT 1120 GMT ON 20 FEBRUARY 1978, INFRA-RED AND VISIBLE PICTURES

The British Isles may be seen at the right-hand side just below the upper timing marker.
(See page 272)

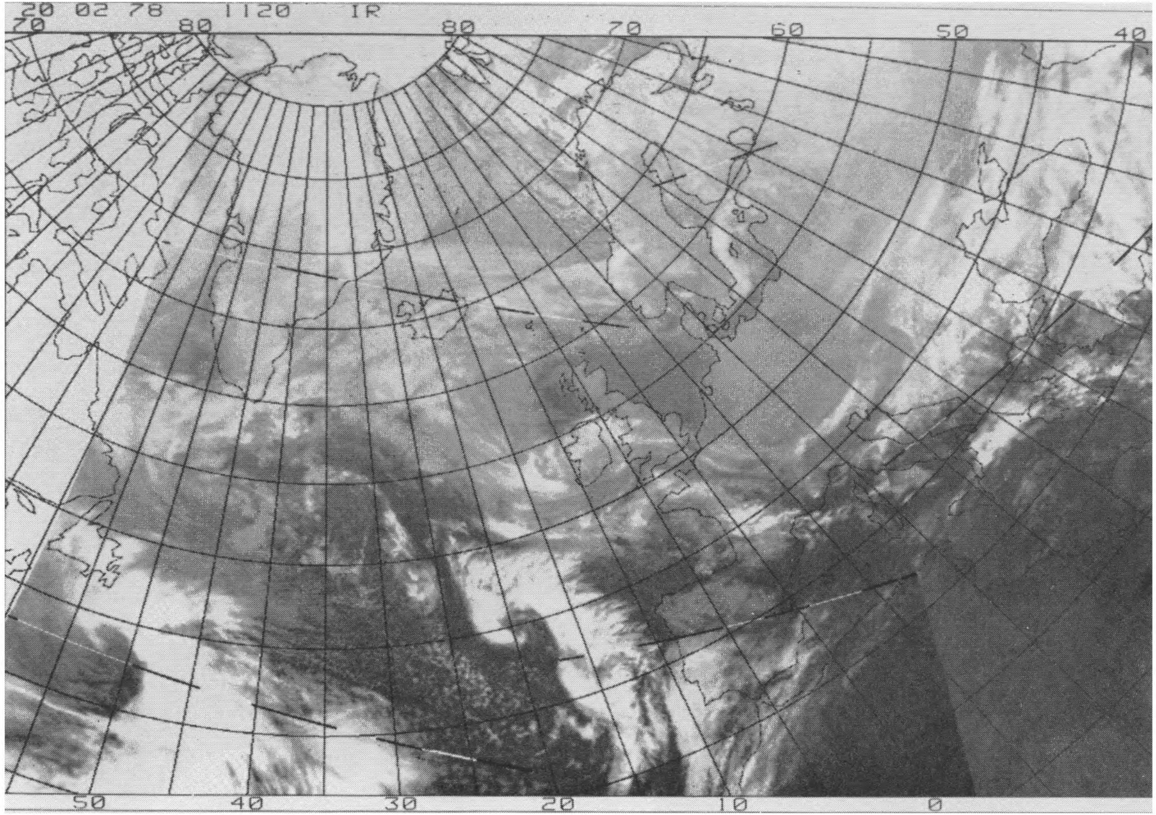

PLATE V (a)—COMPOSITE PICTURE OF THREE ORBITS AFTER PROJECTION ON
20 FEBRUARY 1978 (INFRA-RED)

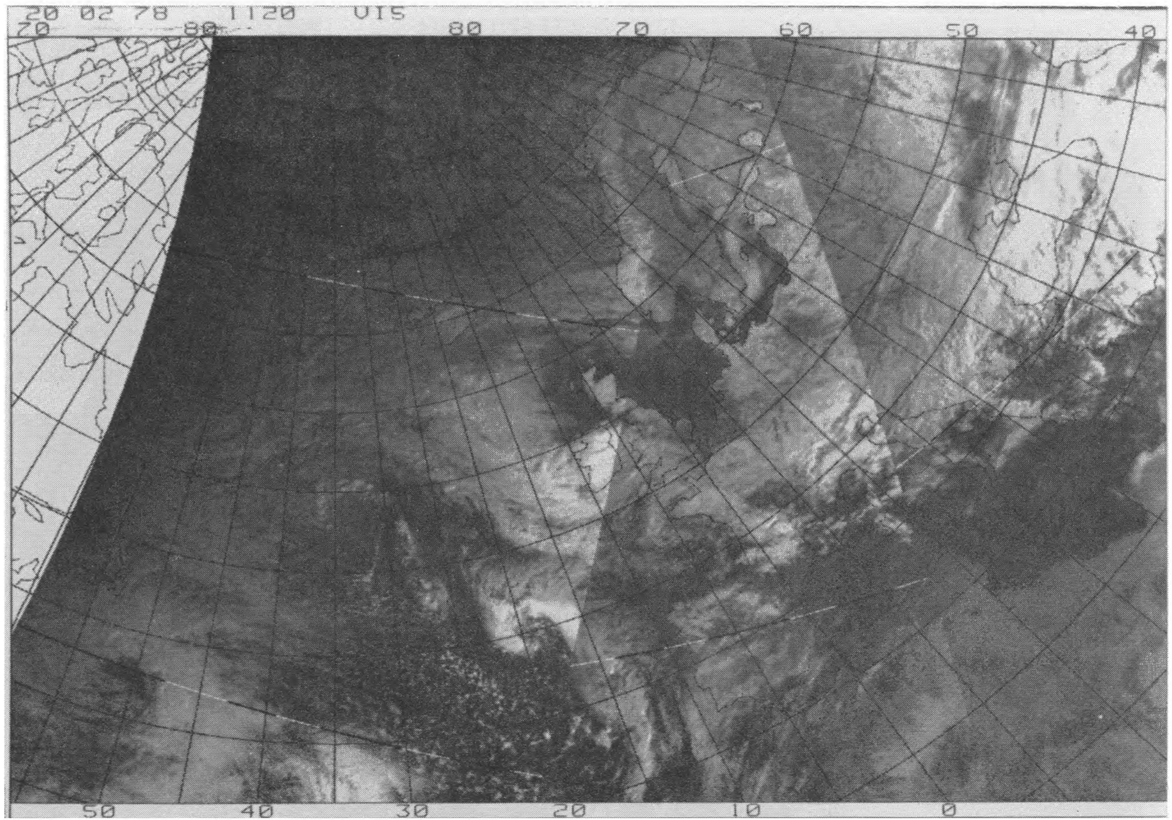

Plate V (b)—Composite picture of three orbits after projection on 20 February 1978 (visible)

(See page 275)

PLATE VI—ALTOCUMULUS MAMMA OVER BRACKNELL (BEAUFORT PARK), 17 SEPTEMBER 1974

Rays from the setting sun illuminating altocumulus mamma from below made an impressive display over Bracknell, Berkshire around 1800 GMT on 17 September 1974. The photograph was taken at 1805 GMT looking westwards towards Beaufort Park, where the 18 GMT observation reported 2/8 stratocumulus at 3000 ft and altocumulus with altostratus, 3/8 at 10 000 ft and 7/8 at 15 000 ft. The surface wind was 330 degrees 2 knots. A weak cold front was to the west, and slight rain had fallen from 1715 to 1735 GMT.

Photograph by C. S. Broomfield

To face page 273

Photograph by C. J. Richards

PLATE VII—SUNSET FROM READING, BERKSHIRE ON 17 JUNE 1973

Photograph by C. J. Richards

PLATE VIII—HEAT THUNDERSTORM AT NAPHILL, HIGH WYCOMBE, BUCKINGHAMSHIRE AT 1930 GMT ON 9 JUNE 1970

Vigorous convection is evident within the cloud mass, with a recently formed anvil canopy spreading out from the cloud top.

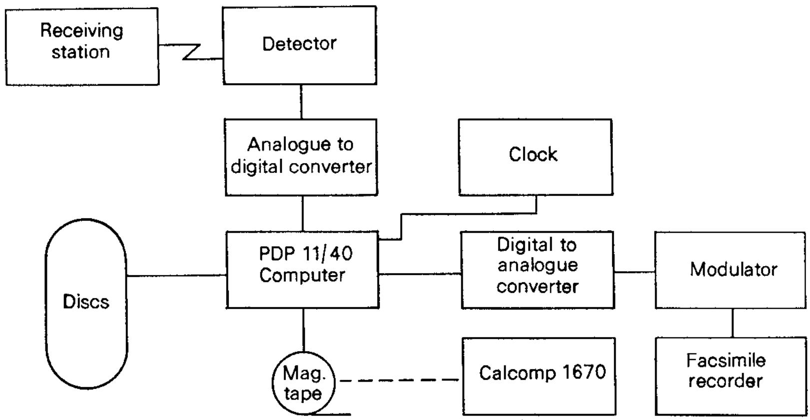

FIGURE 1—SATELLITE PROCESSING SYSTEM

studies of the application of small computer-based systems within the Meteorological Office. In this role it has served as the prototype system for satellite image processing.

There are three main stages, namely data acquisition, data processing and associated map projection, and final output and display in pictorial forms. These are described in a non-technical way; detailed discussion of the special circuitry used for data acquisition, the mathematics of projection and the computer programs is contained in a paper by Wiley and Ponting (1977). The procedure is designed to automate the above-mentioned manual operations, a task well suited to a computer because of the large amount of data processing and arithmetic involved.

DATA ACQUISITION

Data from meteorological satellites are received at Lasham and transmitted by land-line to Bracknell. This transmission is in the form of an amplitude-modulated signal on a 2400 Hz carrier wave, which is the standard facsimile technique. The PDP 11/40 is connected to this line via equipment in the Bracknell Telecommunications Centre. Special circuitry has been built in Met 0 22 which detects the peaks of the carrier thus eliminating, for example, the systematic variations in the carrier frequency due to the Doppler effect. This circuitry also detects a special 300 Hz signal which is used as a marker by both NOAA 5 and Meteosat.

The data are converted to digital values by an analogue-to-digital converter which can be set to sample the incoming data at the peaks of the signal. The digital values are then stored on computer-compatible media (magnetic disc or tape) for subsequent processing. This conversion and storage must be accomplished in real time, that is to say the computer program controlling the flow of data must process each block of data before the reception of the next block of data has been completed.

The United States NOAA 5 satellite has a near-polar orbit (see Figure 2) and views the earth by rotating a scanner on an axis tangential to the orbital path, as shown in Figure 3. Each complete revolution monitors data from an infra-red

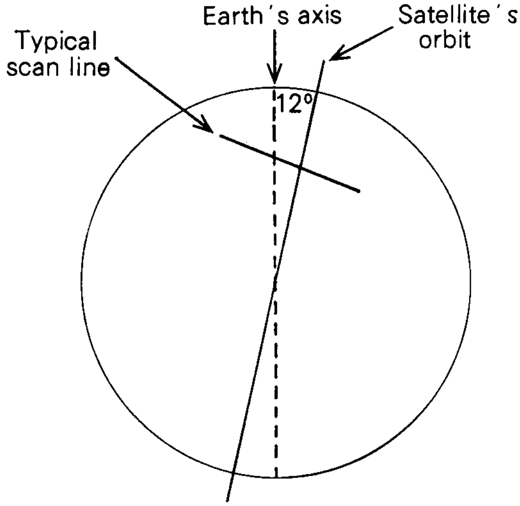

FIGURE 2—NOAA 5 SATELLITE ORBIT

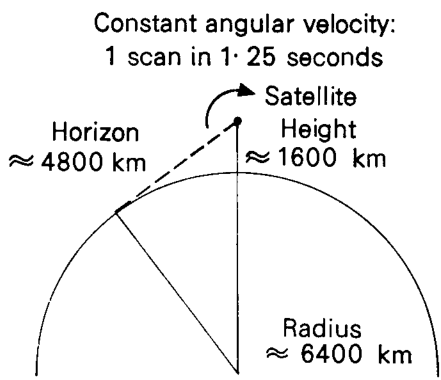

FIGURE 3—SCANNING RADIOMETER SYSTEM

and a visible sensor, half a revolution for each sensor. A complete revolution takes 1·25 seconds, providing 3000 samples (peaks on the 2400 Hz carrier). To reduce the quantity of data to be processed and to speed up the computation, successive pairs of digital values are averaged. After the 300 Hz signal which marks the start of each scan there is a space view, the signal level of which indicates the type of data (black for the visual, white for the infra-red) which follows. The space-view values are also used to check for a genuine signal instead of noise. The digitized information is scaled to be in the range 1 to 254, different values corresponding to different grey levels in the picture, although in practice only part of this range is used. The original resolution of the data directly below the satellite is about 8 km for the infra-red sensor and 4 km for the visible. After averaging, the resolution in the visible is degraded to about 6 km.

The European Space Agency satellite Meteosat transmits successive lines of data every 0·25 second: each scan therefore provides 600 digitized samples. For southern England the resolution is about 6 km east–west and 10 km north–south. For areas further north the resolution becomes progressively poorer; no useful data can be recovered north of about 65°N.

DATA PROJECTION

Once digital data are available they can be processed by computer as required and the results output in pictorial forms or stored for further processing. The following description is for NOAA 5 data only, since the processing for Meteosat is conceptually very similar.

NOAA 5 data are processed to produce pictures as shown in Plate V. The procedure is rather similar to that used by the forecaster in producing a composite nephanalysis. The first orbit (the most eastward) of the day is projected on to the chart, including the edges where detail is blurred owing to the effect of the curvature of the earth on the field of view of the satellite. The next orbit is then added, overlapping at its easterly edge the previous picture. The extent of overlay is to the limits of reasonable resolution of the new picture and was determined in consultation with CFO. Where the computer product differs from the nephanalysis lies in the fact that the latter incorporates data from both the infrared and visible sensors for the day-time orbits whereas the former produces separate pictures for each sensor. The coastline and latitude/longitude grid are superimposed to enable the forecaster to align and locate the final product. In Plate V (b) (visible picture), the boundaries between consecutive orbits are clearly discernible because of the change in illumination from one orbit to the next (about two hours). This effect is especially noticeable in the northern hemisphere winter when the solar elevation is low.

The required map projection is a 1:20 million polar stereographic one as used in CFO. In order to project the satellite picture the position of the satellite has to be determined as accurately as possible. This is done by recording the exact time at which the start of the picture is received and then using previously observed orbital parameters, so-called ephemeris data, provided by the American Space Defense Center, to calculate the position of the satellite. These ephemeris data are often out of date, since they are only received about once a week and are based on ground observations of the orbit made three to four weeks earlier. Also, because of the high speed of the satellite relative to the earth, a small error in the receiving start-time can give a large positional error which would degrade the final product. The relevant date and time are obtained by interrogating a clock, within the PDP 11/40, which tends to lose about one second a day. To maintain the required accuracy of the internal clock it is synchronized each hour with a much more accurate external radio clock transmission from Rugby which gives the month, day, hour and minute every minute with a pulse every second. (The circuitry to receive and decode the Rugby broadcast was specially constructed within Met 0 22.) The ability to correct automatically is especially important following a power failure, since it enables the PDP 11/40 to recover without manual intervention at nights and weekends when it runs unattended.

To reduce the processing time it was assumed that the radius of the earth and of the satellite orbit are constants, and that each scan line is instantaneously produced. For a given point on the map the digital value at the nearest point on the nearest scan line is taken as the required value without further correction. The effect of these approximations is to introduce a very small error not discernible to the forecaster; the processing time is, however, significantly reduced, resulting in earlier availability of the computer products.

Output and pictorial display

The output from the PDP 11/40 is available in several forms depending on the application, namely on facsimile paper, on microfilm (from which photographic enlargements may be produced), on a graphics (VDU) display, or as digital values on any normal computer medium.

For operational use in CFO, hard copy with adequate resolution is required as quickly as possible. A standard facsimile recorder suffices for this. Normally, higher-grade facsimile paper is used because it gives better contrast than the standard grade. The charts, being on the normal CFO scale and map projection, are then directly usable within CFO by forecasters as an aid to analysis; for example, to position surface frontal features, upper troughs, ridges, vortices, and, sometimes, jet streams (see Singleton, 1975) or to produce nephanalyses.

Photographic and archival output can be achieved via the Calcomp 1670 microfilm plotter which is part of the main computing facility of the Meteorological Office, COSMOS. The output from this plotter can be positive for making slides or negative for prints such as the plates in this article. The quality is much better than from a facsimile recorder but takes more than an hour longer to produce.

For output to either of the above devices, the contrast and range of the grey-scale in the picture can be easily adjusted. If a feature is to be enhanced the range can be narrowed to only a few levels round the required level. For example, to emphasize the boundaries of sea-ice, the grey-scale is adjusted so that the difference between the appearance of sea and ice is larger than that in the normal pictures.

For a quick look, particularly for better resolution, a colour visual display terminal attached to the PDP 11/40 is available on which ranges of digital values may be displayed in different colours. Because of the limited resolution of this device only a part of the NOAA 5 satellite picture can be displayed if the full resolution is to be approached. Users can select which part of the picture is to be displayed and which colours correspond to what range of digital values. By these means particular terrains and quite narrow signal ranges can be minutely investigated. No hard copy is, however, available from this terminal.

For research use the digital data themselves are available. Such data on magnetic tape have been supplied to several branches of the Meteorological Office to aid research into and development of applications of satellite image data.

Discussion and concluding remarks

Computer-processed pictures from NOAA 5 have been produced regularly since November 1976. Of the various delays that occur before the data are available to the forecaster, the time taken to acquire the data and output them to a facsimile recorder is unavoidable. Only the times involved in the projection and the method of display are alterable.

The present computer system takes 25 minutes to process one orbit, both infra-red and visible pictures, after which it takes 20 minutes to output the results. The process thus takes at least 45 minutes longer via the computer than the present direct output to a specially modified facsimile recorder. However, the picture may be displayed on a VDU as it is processed, parts within a few minutes of being acquired. If a faster computer were obtained and dedicated to the processing of the satellite image data it would be possible both to speed up and to overlap the projection of the data with the acquisition or output phases, leading to quicker production of the final hard copy.

The present manual gridding procedure is not very accurate since it relies on the positioning of the timing markers and the matching of overlays. With the current computer system the accuracy of the automatic gridding and map projection is consistently good provided that the parameters which describe the orbit of the satellite are updated frequently enough.

The pictures produced by the computer from NOAA 5 data have certain clear advantages over the directly received pictures. For example, it is very easy for the forecaster to follow the movement of cloud systems from day to day as the pictures are always viewable relative to the same chart background. Also, the removal of the distortion caused by the curvature of the earth makes cloud patterns much easier to recognize. Nothing, of course, can be done either way to correct for the loss of resolution caused by the curvature.

The form of the computer output is very flexible. The output can be stored and produced whenever required in a variety of forms, each as often as required. Also the contrast and range of the grey-scale is easily adjusted to emphasize individual features and to reflect the change in illumination with the different times of year.

Acknowledgement

Any project of this size is always a team effort. The author wishes to thank those members of the Systems Development Branch who have assisted in any way with the project and the preparation of this paper.

References

SINGLETON, F. 1975 Human intervention in the operational objective analysis. *Met Mag,* **104,** pp. 323–330.

WILEY, R. L. and PONTING, J. F. 1977 Real time processing of image data from satellites under RSX11-D. *Proceedings of the Digital Equipment Computer Users Society,* **4,** No. 1, pp. 141–146.

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THE RELATIONSHIP BETWEEN VISIBILITY AND SURFACE WIND AT GÜTERSLOH IN WINTER WITH PARTICULAR REFRENCE TO SMOKE POLLUTION

By M. G. WALLER
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SUMMARY

All synoptic observations at Gütersloh for the period December to February 1971–75 were analysed to obtain the percentage frequencies of visibilities below specified limits in relation to the surface wind, distinguishing between occasions with and without precipitation.

These are presented in the form of diagrams. Relatively high frequencies of poor visibility are discussed with particular regard to known smoke sources, and an investigation is made of the effect of precipitation in association with pollution.

INTRODUCTION

Despite local and federal laws governing the control and emission of smoke and pollutants in Germany, visibilities are often seriously reduced near and downwind from industrial areas. It is not uncommon for parts of the industrial Ruhr to experience visibility reduced to fog limits owing to pollution in stable winter conditions.

The visibility at Gütersloh is often reduced by advected smoke pollution which is most noticeable during the winter months. During these months the low-level flying training programmes are often curtailed owing to poor visibility. The runway at Gütersloh is aligned east to west and an additional hazard occurs when atmospheric pollution coincides with cloud-free skies and the sun is at a low elevation. The slant visibility in these cases is often reduced so that a prohibition on visual circuits is enforced.

PURPOSE OF THE INVESTIGATION

It was considered that a statistical analysis of visibility in relation to surface wind speed and direction, limited to the winter months, would indicate the sources of smoke pollution which are close enough to cause serious deteriorations in visibility at Gütersloh. Knowledge of the positions of these smoke sources, together with the frequency of occurrence of winds which transport the pollution to Gütersloh, should be a useful forecasting aid. There may be other stations where a similar analysis may improve the forecasting of visibility. The resulting improved forecasts of visibility could then be given more weight when the daily flying programs were being planned and perhaps lower the number, and therefore the cost, of abortive sorties.

GEOGRAPHICAL SITUATION

Gütersloh airfield lies 72 m above mean sea level on the sandy alluvial flood plain of the River Ems, which is one of the southernmost corners of the North German Plain, bounded in the south by the Sauerland Uplands. To the east the Sauerland Uplands merge with the Westphalian Uplands which consist of a number of ridges extending to the north-west. Thus a natural bowl is formed open from west-south-west to north-west. This is known geographically as Münster Bay.

There are large urban and industrial areas stituated on the low-lying ground of the region, the largest and most well known being the Ruhr industrial complex which lies some 70–130 km to the south-west of Gütersloh.

The significant features of the region are shown in Figure 1.

Factors affecting pollution

The level of pollutant concentration in the atmosphere due to a smoke source is governed, according to Pasquill (1972), by three main factors:

(a) General drift in the prevailing airstream with progressive spreading sideways and vertically.

(b) Chemical and physical transformation in the air-borne stage.

(c) Removal from the atmosphere by various natural processes.

The distribution due to (a) will vary according to a number of factors, the main ones being the strength of the wind and the turbulent and convective motions of the atmosphere. The latter are themselves determined by the strength of the wind, the nature (roughness) of the underlying surface and the stability of the atmosphere.

The analysis presented in this paper ignores a number of these factors and indeed takes no account at all of any factors associated with the pollutant source. The investigation makes use only of the wind, precipitation and visibility during 15 winter months at Gütersloh. It takes no account of time of day or of holidays, both of which are significant factors in the generation of smoke pollution. It takes no account of the trajectory of the air.

Analysis

The 3-hourly synoptic observations of surface wind and visibility at Gütersloh for the period December–February 1971–75 were extracted and classified. Figure 2 shows the frequency of each wind direction (10° sector) expressed as a percentage of the total number of observations extracted. The visibility ranges used were those associated with a colour code which is widely used by military aviation (N.B. The colour code is also dependent on the height of significant cloud, so that the colours denoting visibility ranges in this paper do not always equate to the actual colour state at Gütersloh.) Table I shows the minimum visibility associated with each colour.

Table I—Minimum visibilities associated with the colour code

Colour	Minimum visibility
BLUE	8 km
WHITE	5 km
GREEN	3·7 km
YELLOW	1·8 km
AMBER	0·9 km
RED	ZERO

For wind speeds of 1–6 knots and also for 7 knots or more, the frequencies of the various visibility ranges were obtained for each wind direction (10° sector) as a percentage of the total observations for that particular direction and speed range. The analysis was carried out separately for observations not associated with precipitation and for those associated with precipitation. Observations associated with snow (88) were not included in the analysis. The frequencies were

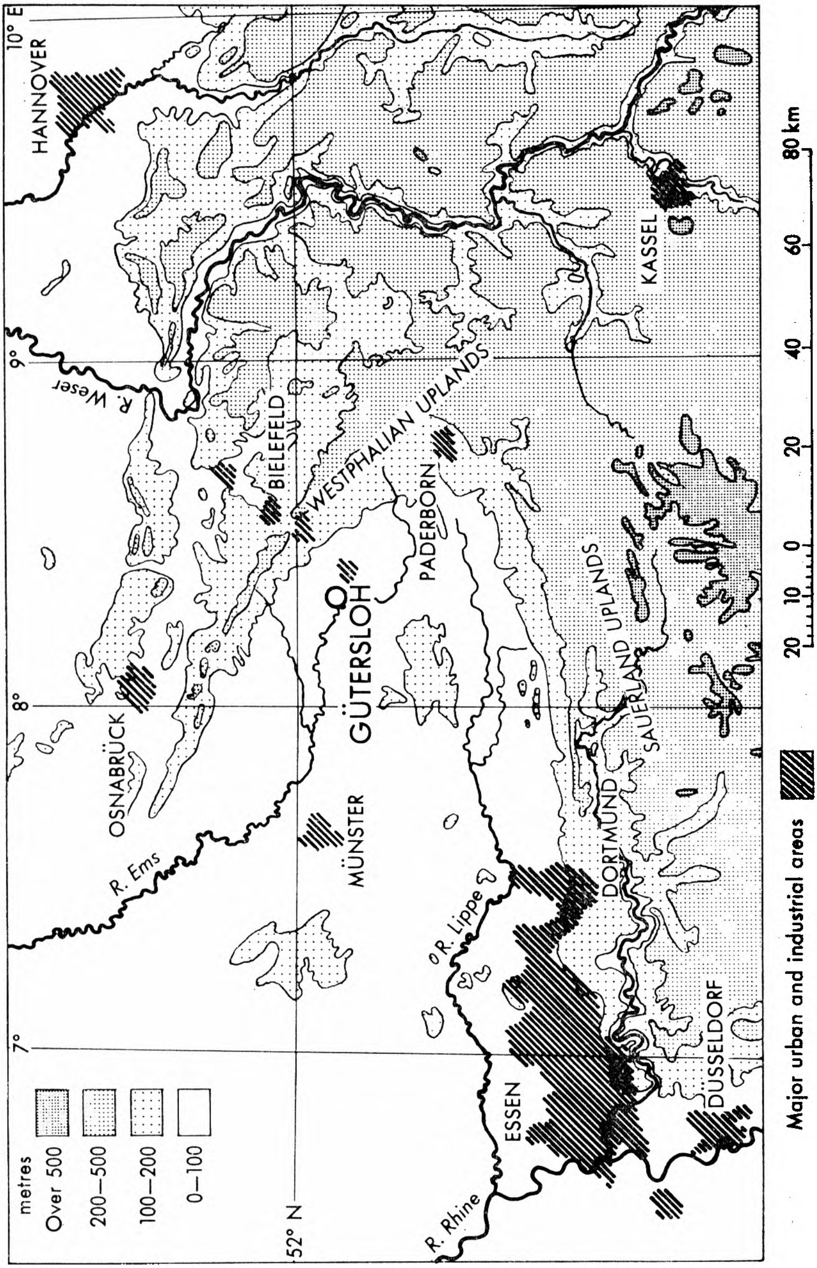

FIGURE 1—MAJOR FEATURES OF THE GÜTERSLOH REGION

plotted against wind direction on a radial type of bar diagram, the visibility ranges shown being limited to the lowest four. The bearing and names of the major urban and industrial smoke-producing areas were marked on the periphery.

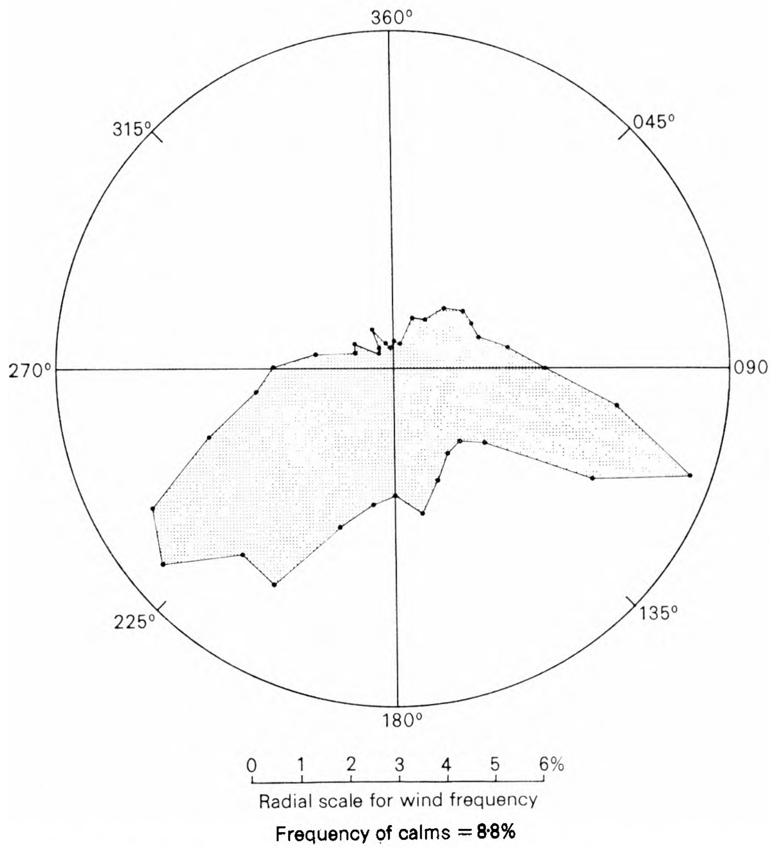

FIGURE 2—PERCENTAGE FREQUENCY OF WIND DIRECTION AT GÜTERSLOH IN WINTER (DECEMBER–FEBRUARY 1971–75)

Figure 3 shows the frequencies plotted against wind direction for 1011 occasions associated with winds of 1–6 knots and no precipitation. The frequency of each wind direction expressed as a percentage of the total number of wind observations (not associated with precipitation) in the range 1–6 knots is superimposed on the diagram as a dot linked to neighbouring values by broken lines.

Figure 4 is a similar diagram for 1630 occasions associated with winds of 7 knots or more and no precipitation. For occasions with precipitation, the 110 observations associated with wind speeds of 1–6 knots were considered too sparse for a diagram to be worth while. However, there were sufficient observations (452) to produce Figure 5 for occasions with wind speeds of 7 knots or more, but wind directions with less than four observations were omitted, restricting the diagram to 100° to 300°. Otherwise the diagram is similar to Figures 3 and 4.

For both Figures 4 and 5, the frequency of each wind direction expressed as a percentage of the total number of wind observations (fulfilling the associated precipitation conditions) in the range 7 knots or more is superimposed on the diagram as in Figure 3.

Discussion and interpretation of diagrams

Wind frequency

The frequency of the wind direction for all cases is presented in Figure 2. The asymmetry of the pattern is most distinctive. The two main peaks are at 230° and 110°. These are no doubt enhanced by topographical effects, but suggest an east-south-east continental winter regime with incursions of milder air from the south-west. The winters included in this analysis have been relatively mild and one would not expect the south-west peak to be as well marked over a longer period.

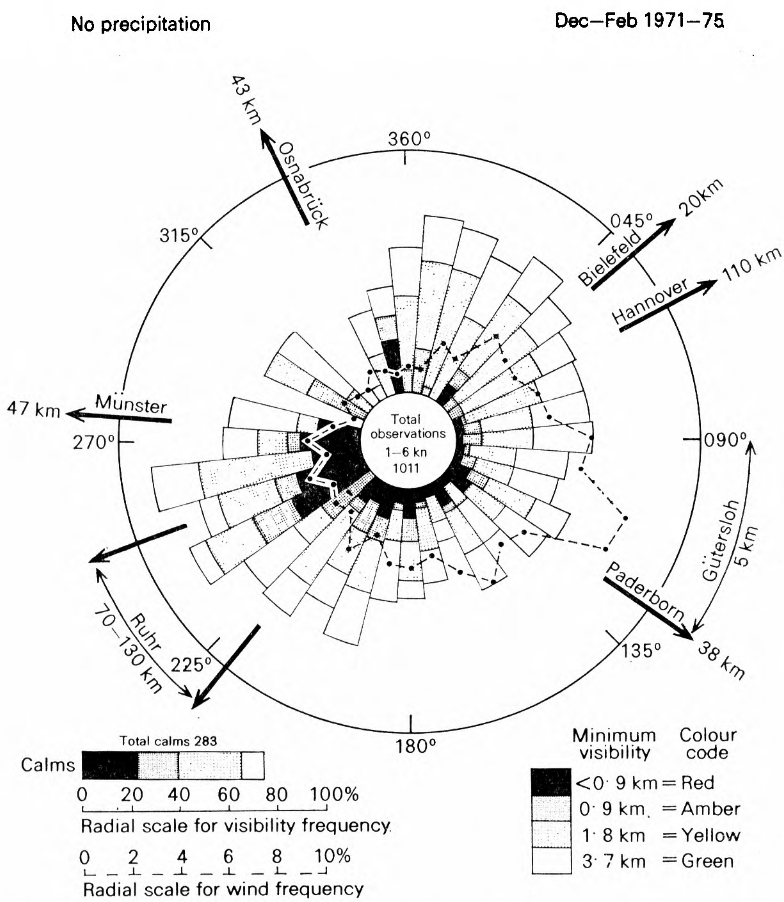

Figure 3—Variation with wind direction of the percentage frequency of various visibilities at Gütersloh in winter (winds 0–6 kn)

Note. The visibility frequencies are not frequencies of colour state.

It has frequently been noticed that with a west-south-west gradient flow, the surface wind at Gütersloh has a tendency to back to just east of south in certain conditions. The analysis reveals a minor peak in frequency in this direction.

A major point of note is that a surface flow from 290° through to 020° was very infrequent during the period analysed.

Figure 3 shows that the frequency of the lighter winds had a peak at 110°–120° which suggests a predominantly quiet anticyclonic flow, whereas in contrast, Figure 5 shows that the frequency of the stronger winds, for occasions associated with precipitation, had a peak at 230° as would be expected with the bulk of the precipitation coming from incursions of milder air from the south-west.

Visibility on occasions with no precipitation

Examination of Figures 3 and 4 reveals the following points:

As might be expected visibility tends to be worse with light winds than with the stronger winds. This is true for nearly all directions.

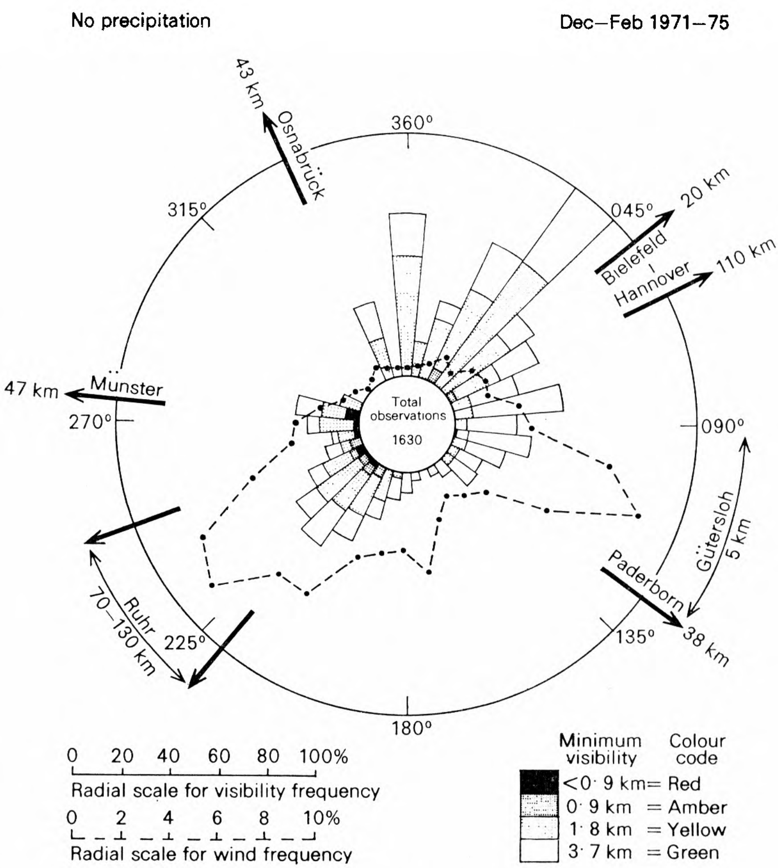

FIGURE 4—VARIATION WITH WIND DIRECTION OF THE PERCENTAGE FREQUENCY OF VARIOUS VISIBILITIES AT GÜTERSLOH IN WINTER (WINDS ≥ 7 kn)

Note. The visibility frequencies are not frequencies of colour state.

With light winds the highest frequencies of poor visibilities are in the sector south-west to west and are undoubtedly associated with Ruhr pollution.

The stronger wind diagram shows the higher frequencies of poor visibilities appearing in several well-defined sectors. The two major peaks are centred on 040° and 220° with minor peaks around 270°, 340° and 360°. Relating these peaks to the major urban and industrial areas the 040°, 220° and 270° peaks are backed by some 5–20 degrees from the Bielefeld–Hannover, Ruhr and Münster areas respectively. In particular the 220° peak is backed by about 15 degrees from the mean direction of the Ruhr industrial area which lies between about 220° and 250°. It is concluded that these peaks are due to the advection of pollution from these areas although the precise track is complicated by the terrain. It should also be mentioned that the surface wind at Gütersloh is often more backed from the gradient wind direction than might be expected.

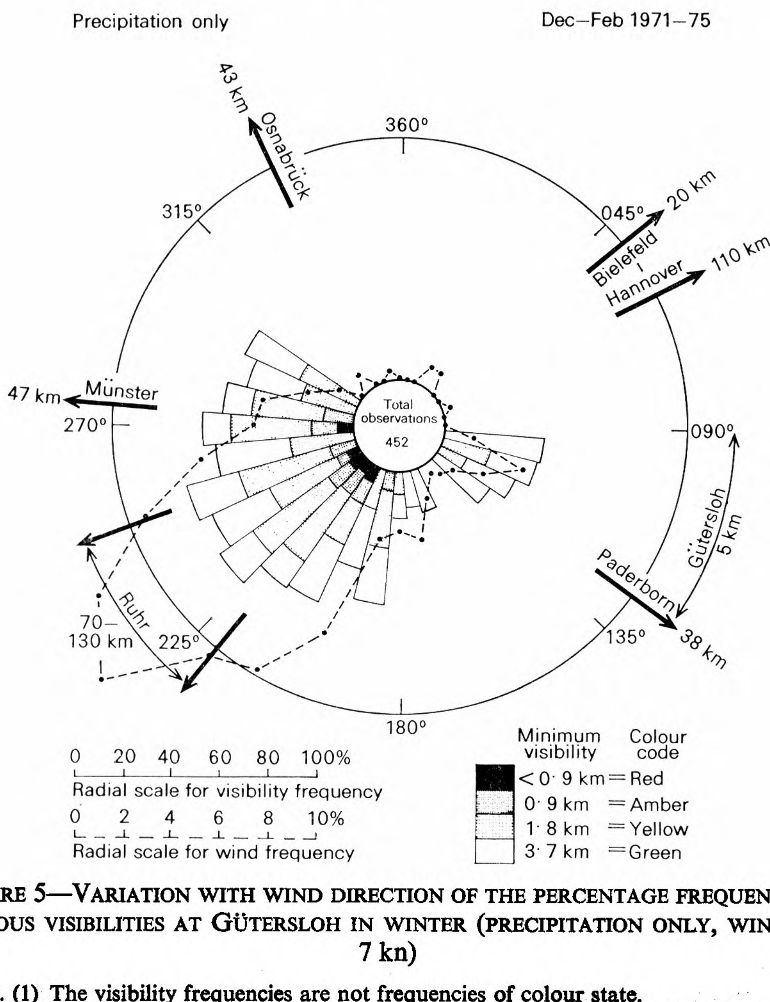

FIGURE 5—VARIATION WITH WIND DIRECTION OF THE PERCENTAGE FREQUENCY OF VARIOUS VISIBILITIES AT GÜTERSLOH IN WINTER (PRECIPITATION ONLY, WINDS ⩾ 7 kn)

Notes. (1) The visibility frequencies are not frequencies of colour state.
(2) The visibility frequencies are shown for the wind directions 100°–300° only, i.e. for wind directions with four or more observations.

The minor peak at 360° is difficult to relate to pollution but the Hannover area is thought to be the source. In marked stable conditions an east-north-east gradient flow usually gives a wind of north-north-east at Gütersloh. However, on some occasions the surface wind backs by 90 degrees or more under the influence of the Westphalian Uplands and is reported as 360° or even 350° at Gütersloh. On these occasions pollution from the Hannover area could reach Gütersloh after a long complex trajectory.

Visibility on occasions with precipitation

Caution is needed in interpreting the results of this section as the number of observations during the period was small.

In order to investigate the effect of precipitation in association with pollution, a comparison was made between Figures 4 and 5. This was limited to wind direction from 210°–260° for which the visibility frequencies were based on a reasonable number of observations for both diagrams. Within these limits, it has been shown that the wind direction associated with the peak frequency of poor visibility, and presumably with the greatest smoke pollution effect due to the Ruhr area, is backed some 15 degrees from the direction of the centre of the Ruhr area which extends from 220° to 250°. Assuming that this backing applies to the Ruhr area as a whole, the sector 210°–230° should be favourable for pollution whilst that for 240°–260° should not. The contrast is well marked in Figure 4 and to a lesser degree in Figure 5. To examine in more detail the effect of precipitation on visibility reference is made to Table II.

TABLE II—A COMPARISON OF THE EFFECT OF PRECIPITATION ON VISIBILITY FREQUENCIES FOR WIND DIRECTIONS ASSOCIATED WITH HIGH AND LOW SMOKE POLLUTION FROM THE RUHR (WINDS $\geqslant$ 7 kn)

		Percentage frequency of visibility categories							
		No precipitation				Precipitation			
		G	Y	A	R	G	Y	A	R
High pollution	210°	34	21	4	0	61	36	16	6
	220°	41	23	5	2	63	49	15	4
	230°	36	26	4	1	72	47	16	5
Average		37	23	4	1	65	47	16	5
Low pollution	240°	25	18	6	3	67	40	9	4
	250°	15	9	5	2	71	49	10	0
	260°	11	9	2	2	57	25	0	0
Average		17	12	4	2	65	38	6	1

N.B. G = Green or less i.e. 0–5 km. Y = Yellow or less i.e. 0–3·7 km.
A = Amber or less i.e. 0–1·8 km. R = Red i.e. less than 0·9 km.

For the sector 210°–230°, the frequencies of the various visibility categories are all higher for occasions with precipitation. The increase for the colour code green or less is from about 30–40 to 60–70 per cent. For the sector 240°–260°, the frequencies for the various visibility categories, excepting colour code red, are also higher for occasions with precipitation. Here, however, the increase in frequency for colour code green or less is even greater, i.e. from about 10–20 to 60–70 per cent, reaching about the same frequency as for the other sector. It is concluded that precipitation has a much greater reducing effect on visibility when the air is not already heavily polluted. It is noteworthy, however, that the incidence of really poor visibility at Gütersloh (when the wind is 7 kn or more) is highest when high pollution and precipitation occur together. This is contrary to Jefferson (1961) whose results for Manchester Airport suggested that when the visibility is already only moderate due to other causes such as smoke haze, no further reduction is to be expected. The Manchester figures, however, took no account of wind speed. It is also contrary to Ross (1967) who suggested that in industrial areas the haze may be thick enough at times to obscure the effects of precipitation on visibility. While this may be true the present investigation does not support the suggestion.

There is some evidence of a minor peak at 110° which could be associated with local pollution from Gütersloh town. The peak is, however, of doubtful significance because of the small number of observations on which the frequencies for the adjoining sectors were based.

Experience of forecasting at Gütersloh suggests that cold frontal clearances are often delayed, owing to the up-slope and funnelling between the Westphalian and Sauerland Uplands. This may account for the continuing high frequencies round to 300°, although the 290° and 300° frequencies were based on only nine and four observations respectively and may not be significant.

CONCLUSIONS

Although only a limited analysis of visibility in relation to surface wind at Gütersloh was undertaken, it has served to indicate the major sources of atmospheric pollution that affect the visibility. The diagrams presented can be used in winter as a forecasting aid, in that greater weight can be given to the surface wind when forecasting visibility in various synoptic conditions.

The diagrams can also help to predict the visibility in the surrounding area. For instance, if Gütersloh is experiencing a visibility within 'green' limits and has a surface wind of 200°, there would be a high probability of the visibility being within 'yellow' limits or worse in a band orientated in a SW/NE direction and about 70 km in width situated just to the west of Gütersloh. This is on the assumption that the Ruhr pollution plume is being advected just to the west of Gütersloh.

The forecasting of the surface wind at Gütersloh is a difficult problem in itself owing to the effect of the surrounding terrain, and the value of the diagrams will probably be most apparent in short-period forecasting. A number of visibility deteriorations occur in winter during mid-morning similiar to those that affect some airfields in eastern England (Saunders, 1971). Reference to the diagrams will show if the onset of flow, due to the diurnal increase in wind speed and turbulence after sunrise, is from a direction from which pollution may be advected.

ACKNOWLEDGEMENT

The author is grateful to the staff of the meteorological office at Gütersloh and to Mr C. L. Hawson for their assistance and advice while preparing this paper.

REFERENCES

JEFFERSON, G. J. 1961 Visibility in precipitation. *Met Mag*, **90**, pp. 168–174.

PASQUILL, F. 1972 Factors determining pollution from local sources in industrial and urban areas. *Met Mag*, **101**, pp. 1–7.

ROSS, S. M. 1967 Visibility in precipitation at Kinloss. *Met Mag*, **96**, pp. 19–22.
SAUNDERS, W. E. 1971 Visibility deterioration during winter mornings. *Met Mag*, **100**, pp. 149–155.

REVIEW

Journal of Arid Environments, Volume 1, Number 1, March 1978. 250 mm × 175 mm, pp. 104, *illus*. Academic Press, London, New York and San Francisco. Price: Volume 1, four issues, inland £14.50, inclusive of postage and packing; abroad £18.15, inclusive of postage and packing.

This is the first number of a new journal published by the Academic Press under the editorship of Professor J. L. Cloudsley-Thompson of Birkbeck College, University of London. The new journal, according to an editorial, is intended as a forum for multidisciplinary and interdisciplinary dialogue where research workers, whose major interests lie in the desert environment and the problems it poses, may publish the results of their research, and where comprehensive reviews may also be published that will be intelligible to advanced students, technologists, administrators and research workers regardless of their own particular specializations and disciplines. In addition to an Associate Editor (Anne Cloudsley) the editorial board comprises 19 names almost all of whom appear to be specialists in the life-sciences. There is no professional meteorologist on the board, but there are three geographers with interests in climatology. However, the first paper in the journal, by Sharon E. Nicholson and entitled 'Climatic variations in the Sahel and other African regions during the past five centuries' is based on work done at NCAR, Boulder, Co. There is little or no meteorology in the other seven papers—or in the list of nine forthcoming papers—but they have a wide range of interest, covering topics as varied as Islamic water law, the diversity of rodent species in northern Israel, and the decomposition of elephant carcases in Kenya. There are also nine full-length book reviews as well as a 'shorter notice'.

From a perusal of the first number it seems that the *Journal of Arid Environments* is unlikely to contain much of professional interest to meteorologists, although the occasional article on climatology may well appear from time to time.

R. P. W. LEWIS

AWARD

We note with pleasure that the 23rd International Meteorological Organization Prize for outstanding work in meteorology and international collaboration has been awarded to Dr Alf E. G. E. Nyberg, Director-General of the Swedish Meteorological and Hydrological Institute from 1955 to 1977. Dr Nyberg served as President of the WMO Regional Association for Europe from 1956 to 1963 and as President of WMO from 1963 to 1971. He has undertaken several technical co-operation missions to developing countries on behalf of WMO and has published many papers on meteorology, in particular on aerological and synoptic questions and on the relations between meteorological factors and atmospheric pollution.

OBITUARY

We regret to record the death on 3 April 1978 of Mr D. H. Philips, Higher Scientific Officer, of the Observational Requirements and Practices Branch (Met O 1). Mr Philips joined the Office as an Assistant in September 1947, and served in a wide variety of stations at home and overseas, including weather ships and radiosonde and CRDF establishments; he also worked for several years in the Editing Section (Met O 18b). He was promoted to HSO in October 1976 and at the time of his death was in charge of the section that deals with Automatic Weather Stations.

We regret to record the death on 15 April 1978 of Mr W. Conner, Scientific Officer, of the Civil Airport, Benbecula. Mr Conner joined the Office in April 1941 and served at a large number of outstations in the United Kingdom and also, for a time during the war, in Iceland. While at Benbecula he took a leading part in organizing youth movements, and helped to arrange various outdoor activities for them.

THE METEOROLOGICAL MAGAZINE

NO. 1274 SEPTEMBER 1978 VOL. 107

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, and marked 'For Meteorological Magazine'.

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1 monthly **Annual subscription £13.14 including postage**

Dd. 595890 K15 9/78

ISBN 0 11 724803 7
ISSN 0026–1149

Met.O.915
METEOROLOGICAL OFFICE

the meteorological magazine

OCTOBER 1978 No 1275 Vol 107
Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.915

THE METEOROLOGICAL MAGAZINE

No. 1275, October 1978, Vol. 107

551.591.31 (422.9): 656.1

VARIABILITY WITH TIME OF POOR VISIBILITY BESIDE A MOTORWAY

By S. G. SMITH
(Meteorological Office, Bracknell)

SUMMARY

Analysis has been carried out of transmissometer readings recorded during occasions of poor visibility over the period from November 1974 to May 1975 beside the M4 motorway near Theale in Berkshire. Probabilities of given changes in visibility from various initial visibility ranges over different time intervals have been determined separately for rises and falls in visibility. Variations in these probabilities due to time of day and type of fog have also been explored.

INTRODUCTION

The occurrence of serious motorway accidents in recent years has increased public awareness of the dangers associated with sudden changes in visibility both in short time intervals and over short distances. This study has investigated temporal changes in visibility using readings taken beside the M4 motorway near Theale, Berkshire during the 1974–75 winter.

Similar work was carried out by Le Grice (1974, unpublished) using data from the Theale site and by Briggs (1969) using data from Heathrow Airport. The present analysis differs from that of Briggs in that a distinction is made between rises and falls in visibility; various extensions have also been made to the work of both Briggs and Le Grice.

Plots of air temperature, wind speed and humidity (which were all observed concurrently with visibility) were also examined in a search for associations which might help to predict short-term changes in visibility. The wet-bulb readings from which the humidity values were in part derived were found to be too unreliable during occasions of high humidity (often apparently higher than associated dry-bulb readings) to allow quantitative analysis. Short-period changes in the other parameters largely occurred at the same time as changes in visibility and so did not provide worthwhile precursor signals of short-term visibility changes.

INSTRUMENTATION AND DATA

The visibility recording instrument used was a modified Meteorological Office transmissometer with 100 m baseline and 40 second time constant. Voltage readings associated with the sensor were transmitted by Post Office land-line every 15 minutes as routine. In addition, whenever the visibility was below 900 m transmissions were made every 2 minutes. Records ran from 15 November 1974 until 15 May 1975; in theory they were continuous, but in practice there were breaks due to transmission or instrumental faults. The 2 minute and 15 minute records were separate, so that occasionally when visibility was below 900 m only the 15 minute record was available. As the type of transmissometer used is incapable of discrimination below 50 m, all such readings were counted as 50 m.

Site

The transmissometer was situated on the north side of the M4 motorway about 400 m west of the Burghfield Road overbridge (National Grid Reference SU 669702) at a height of 45 metres above mean sea level. It stood 1·2 m above the road surface and 4 m from the hard shoulder of the motorway with the sensor facing east parallel to the motorway. The site is in rather flat surroundings with areas of lying water in the vicinity. A large conurbation including the town of Reading and several industries lies about 8 km to the north-east.

Data analysed

The analysis covered all periods during which the visibility was less than 1500 m and also the 70 minutes following each of these periods. Reference to the *Daily Weather Reports* indicated that none of these incidents was caused by rain; however, five were associated with snow and these five were omitted from this study. An 'occasion of fog' was defined as a period of visibility less than 800 m (excluding the above five episodes). Periods when the visibility rose above 800 m but failed to exceed 1500 m before returning below 800 m within 70 minutes were treated as one 'occasion'. Out of 182 days covered by the study, there were 26 'occasions of fog' totalling 111 hours on 26 different days; a total of 1730 visibilities were recorded in the range 50–799 m (including 375 observations of below 50 m which were counted as 50 m).

Method of analysis

Each visibility reading below 800 m (including those below 50 m taken as 50 m) was treated in turn as an initial visibility and the readings were first grouped into five classes (50–99, 100–199, 200–399, 400–599 and 600–799 m) which were analysed separately. Each initial visibility was then compared with readings made after time lags of 2,4,6,10,15,20,30,45 and 60 minutes, a tolerance of $\pm$ 10 per cent of each lag being allowed; the change in visibility in each case was then expressed as a percentage of the initial visibility and allocated to one of 17 categories of change (0–9, 10–19, ... 90–99, 100–149, ... 350–399, $\geqslant$ 400 per cent). Rises and falls in visibility were analysed separately for each class and lag. All comparisons for which *both* observations had been counted as 50 m were excluded from the analysis. To reduce the effects of missing values, linear interpolation, or if this was not possible, linear extrapolation from the last two readings, was used to estimate missing values, provided that the estimated visibilities were for times within 15 minutes of at least one of the available observations. For any particular initial visibility class and time lag the total of the estimated values was generally less than 10 per cent (nearly all less than 20 per cent) of the actual values. Any estimated values of less than 50 m were set to 50 m.

It should be noted that the greatest possible reduction in the initial visibility is 100 per cent, but that there is no such limit to the possible percentage increase in visibility. This skew effect is enhanced by the lower limit of 50 m in the resolution of the instrument, especially for the lower initial visibility classes; for example the maximum fall which can be measured in the 600–799 m initial visibility class is from 799 to 50 m, that is to say 94 per cent of the initial visibility, but it is only 50 per cent for the 50–99 m class and zero for the lowest values in this class.

Two forms of analysis were used. Method (i) treated the rises and falls as known separate categories within each initial visibility class and time lag. Method (ii) treated rises and falls separately but as percentages of the total of rises and falls together within each initial visibility class and time lag. For both methods cumulative percentages of occasions for which the percentage change in visibility exceeded a given value were derived for each initial visibility class and time lag (rises and falls separately).

Results

An example showing the results of the type (i) analysis for the 200–399 m class and for selected time lags (all hours of day) is given in Figure 1. The values of the ordinate are percentage probabilities of occurrence of specified changes in visibility, given that either a fall or a rise will occur. The graph illustrates the general findings that the greater the time lag the greater the probability of a given percentage change in visibility (true for rises and falls) and that the probability of a given percentage change in visibility occurring is greater for rises than for falls. Also deduced from graphs based on the type (i) analysis (not shown) is the fact that the greater the initial visibility the smaller is the probability of large changes, more especially for rises than for falls.

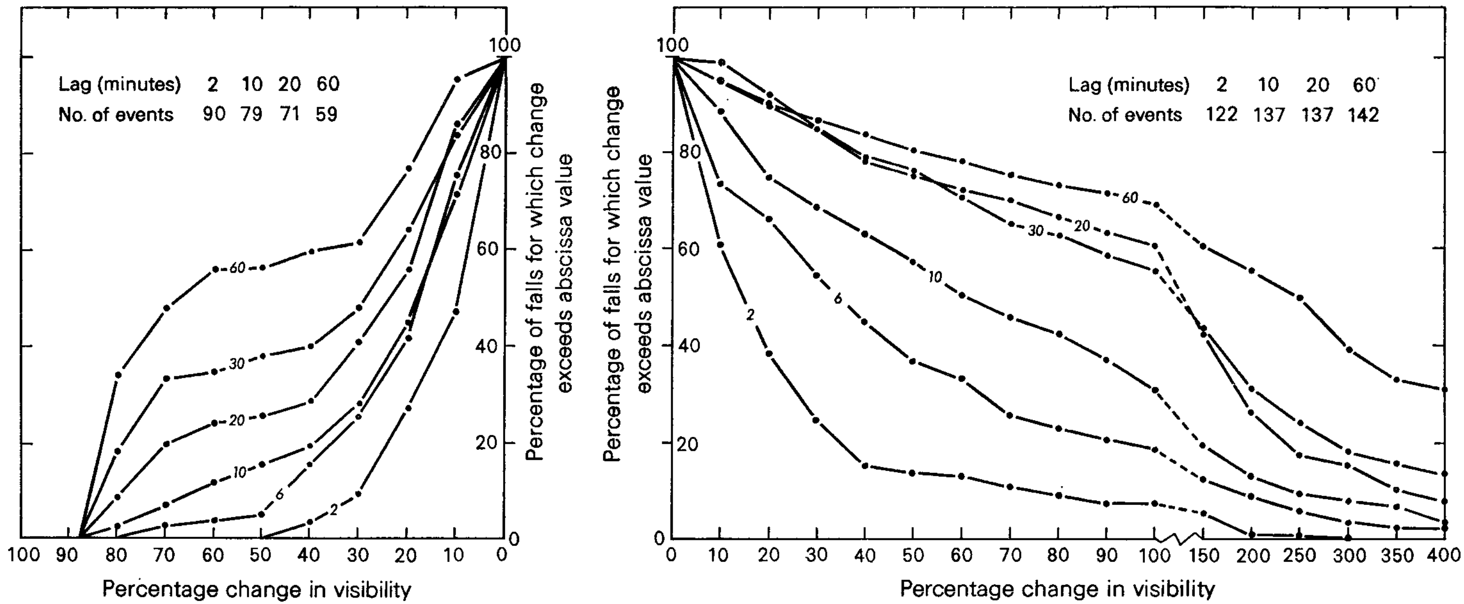
The above remarks relate to analyses based upon all hours of the 24 hour cycle taken together. They require modification when diurnal effects are considered (see section below headed 'Diurnal variations in probabilities of visibility changes').

Table I and Figure 2 present results for the type (ii) method, again for all hours of day. Table I displays the results for five time lags and all initial visibility classes and Figure 2 shows these results graphically for all time lags for the 200–399 m class only. The values in the body of Table I, corresponding to the ordinate on the graph of Figure 2, are percentage probabilities that, say, a fall in visibility will exceed a given percentage change, it not being known in advance whether in fact a fall will occur. Thus for a visibility in the 200–399 m class the probability is slightly above 0·05 that after 10 minutes there will be a fall exceeding 50 per cent of the initial visibility.

These type (ii) results, for all visibility classes considered, show similar features to those of the type (i) results described above, although owing to the small number of falls (relative to rises) in the 50–99 m class, the probabilities of falls from this initial class are considerably less than for higher initial visibilities.

Diurnal variations in probabilities of visibility changes

To study whether the various probabilities associated with visibility change reveal any diurnal variations each initial visibility was classified into one of six 'time-of-day' periods (00–04, 04–08, ... 20–24 h GMT) and the analysis



(a) FALLS (b) RISES

FIGURE 1—PROBABILITY THAT (a) A FALL (b) A RISE WILL OCCUR EXCEEDING A GIVEN PERCENTAGE VISIBILITY CHANGE AFTER SPECIFIED TIME LAGS

Probabilities are expressed as percentages of corresponding total number of (a) falls (b) rises. All hours of day. Initial visibility in range 200–399 m. Italic figures on curves indicate time lags in minutes.

TABLE I—PERCENTAGE PROBABILITY THAT A FALL OR RISE IN VISIBILITY WILL OCCUR THAT EXCEEDS GIVEN PERCENTAGE VISIBILITY CHANGES AFTER SPECIFIED TIME LAGS, FOR DIFFERENT INITIAL VISIBILITIES

Time lag *minutes*	Initial vis. *metres*		Percentage visibility change 10	20	30	40	50	60	70	80	90	100	150	200	250	300	350	400	Total no. of occasions
	50–99	F	11·6	5·0	2·5	0·8	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	42
		R	19·8	9·9	5·0	3·3	1·7	1·7	1·7	1·7	0·8	0·8	0·8	0·8	0·8	0·8	0·8	0·8	79
	100–199	F	14·5	7·3	3·6	1·8	1·8	1·8	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	24
		R	38·2	25·5	18·2	12·7	5·5	3·6	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	31
2	200–399	F	19·8	11·3	3·8	1·4	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	90
		R	34·9	22·2	14·2	9·0	8·0	7·5	6·1	5·2	4·2	4·2	3·3	0·5	0·5	0·0	0·0	0·0	122
	400–599	F	15·7	7·3	2·4	2·0	1·2	0·4	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	116
		R	17·7	8·1	4·4	2·0	1·2	0·8	0·4	0·4	0·4	0·0	0·0	0·0	0·0	0·0	0·0	0·0	132
	600–799	F	8·1	3·8	1·7	1·1	0·4	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	238
		R	10·9	4·3	1·5	0·6	0·6	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	232
	50–99	F	18·7	9·0	3·7	2·2	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	38
		R	53·0	32·1	26·1	19·4	18·7	16·4	12·7	11·9	9·0	7·5	7·5	4·5	4·5	3·7	3·7	3·7	96
	100–199	F	25·0	21·4	16·1	8·9	3·6	3·6	1·8	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	20
		R	51·8	50·0	48·2	39·3	35·7	35·7	30·4	28·6	28·6	21·4	12·5	8·9	5·4	3·6	3·6	1·8	36
10	200–399	F	25·9	16·2	10·2	6·9	5·6	4·2	2·3	0·9	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	79
		R	56·0	47·7	43·5	40·3	36·6	31·9	29·2	26·9	23·6	19·4	12·5	8·3	6·0	5·1	4·2	2·3	137
	400–599	F	26·5	19·4	17·4	10·7	4·0	0·4	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	112
		R	39·1	22·9	18·2	15·8	13·0	8·7	6·7	5·1	4·7	4·3	2·8	2·0	0·8	0·0	0·0	0·0	141
	600–799	F	21·9	9·3	6·1	4·2	2·7	2·3	1·9	0·6	0·4	0·0	0·0	0·0	0·0	0·0	0·0	0·0	195
		R	33·3	16·8	10·1	7·4	5·5	4·8	3·6	3·2	1·9	1·3	0·2	0·2	0·2	0·0	0·0	0·0	280

F = Falls R = Rises

TABLE I—*continued*

Time lag *minutes*	Initial vis. *metres*		Percentage visibility change 10	20	30	40	50	60	70	80	90	100	150	200	250	300	350	400	Total no. of occasions
	50–99	F	18·5	10·6	8·6	2·6	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	40
		R	60·3	53·0	41·1	31·8	29·1	24·5	20·5	19·9	17·2	17·2	15·9	13·2	11·3	9·9	8·6	7·9	111
	100–199	F	27·3	25·5	21·8	16·4	14·5	5·5	1·8	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	19
		R	56·4	56·4	52·7	49·1	49·1	45·5	45·5	41·8	41·8	40·0	27·3	20·0	18·2	10·9	9·1	3·6	36
20	200–399	F	29·3	18·8	14·4	9·6	8·7	8·2	6·7	2·9	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	71
		R	62·5	59·1	55·8	51·4	49·5	47·6	46·2	43·8	41·8	39·9	27·9	17·3	11·5	10·1	6·7	5·3	137
	400–599	F	28·8	23·6	13·2	10·0	6·0	3·2	2·4	2·4	1·2	0·0	0·0	0·0	0·0	0·0	0·0	0·0	96
		R	49·6	35·2	23·6	19·6	17·2	14·4	12·8	12·0	11·2	9·6	6·4	3·6	2·8	2·4	2·0	0·8	154
	600–799	F	27·4	15·2	8·8	7·5	6·6	4·7	3·0	1·9	0·2	0·0	0·0	0·0	0·0	0·0	0·0	0·0	206
		R	42·4	28·5	18·8	12·6	7·9	7·3	6·4	5·8	5·4	5·1	3·0	1·3	0·6	0·2	0·2	0·0	261
	50–99	F	19·5	12·8	7·9	3·7	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	43
		R	67·7	59·1	52·4	43·3	39·6	32·9	29·9	27·4	26·2	25·0	22·6	18·3	16·5	14·6	14·0	12·8	121
	100–199	F	30·9	30·9	27·3	21·8	9·1	7·3	1·8	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	19
		R	58·2	58·2	56·4	56·4	56·4	56·4	54·5	52·7	52·7	50·9	43·6	38·2	36·4	32·7	27·3	25·5	36
30	200–399	F	25·6	19·6	14·6	12·1	11·6	10·6	10·1	5·5	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	61
		R	68·3	63·8	58·8	54·8	52·8	48·7	45·2	43·7	40·7	38·7	30·2	21·6	16·6	12·6	11·1	9·5	138
	400–599	F	26·8	22·4	19·1	17·5	12·2	5·7	5·3	5·3	2·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	83
		R	57·3	47·2	37·4	32·1	27·2	22·8	20·3	18·7	15·9	13·4	11·0	8·9	5·7	4·5	3·7	2·8	163
	600–799	F	27·1	16·6	10·1	8·7	6·7	3·6	1·8	1·6	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	167
		R	45·3	35·7	24·9	16·8	13·9	10·5	9·4	8·5	7·6	7·0	4·9	3·1	0·7	0·2	0·0	0 0	279

TABLE I—*continued*

Time lag *minutes*	Initial vis. *metres*		Percentage visibility change 10	20	30	40	50	60	70	80	90	100	150	200	250	300	350	400	Total no. of occasions
	50–99	F	18·7	13·6	8·4	2·8	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	48
		R	71·5	69·2	66·4	60·3	57·5	54·2	48·6	45·3	42·1	40·7	37·4	34·6	33·2	32·2	31·3	30·8	166
	100–199	F	25·9	24·1	20·4	20·4	14·8	9·3	3·7	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	14
		R	68·5	66·7	64·8	63·0	57·4	53·7	53·7	53·7	50·0	48·1	42·6	42·6	42·6	42·6	42·6	40·7	40
60	200–399	F	27·9	22·4	17·9	17·4	16·4	16·4	13·9	10·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	59
		R	67·2	63·7	61·2	59·2	56·7	55·2	53·2	51·7	50·7	48·8	42·8	39·3	35·3	27·9	23·4	21·9	142
	400–599	F	28·9	25·5	22·6	19·7	17·2	15·1	14·6	13·8	3·8	0·0	0·0	0·0	0·0	0·0	0·0	0·0	74
		R	64·0	55·2	46·9	40·2	36·8	32·2	29·7	28·5	23·8	22·2	17·2	15·1	8·8	5·4	4·2	2·1	165
	600–799	F	29·6	22·1	12·4	9·4	8·7	7·5	5·6	4·7	4·2	0·0	0·0	0·0	0·0	0·0	0·0	0·0	163
		R	52·1	41·3	33·3	25·8	20·0	15·3	12·7	10·6	9·9	9·2	6·3	5·4	2·8	2·3	1·6	1·2	263

F = Falls R = Rises

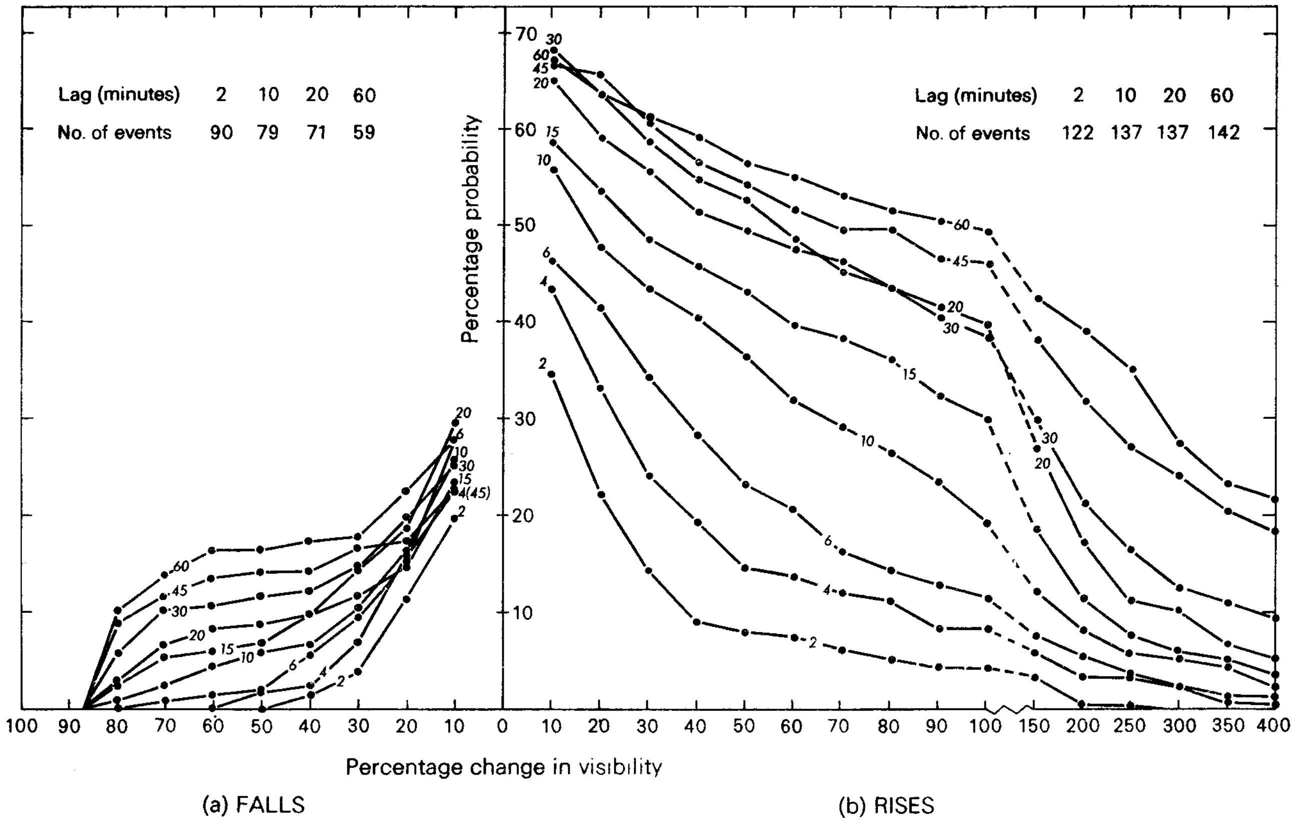


FIGURE 2—PROBABILITY THAT (a) A FALL (b) A RISE WILL OCCUR EXCEEDING A GIVEN PERCENTAGE VISIBILITY CHANGE AFTER SPECIFIED TIME LAGS

Probabilities are expressed as percentages of total numbers of falls and rises combined. Other remarks as for Figure 1.

repeated using the type (ii) method. Figures 3 and 4 display results for the 200–399 m class for the 04–08 and 20–24 h periods respectively and Figures 5 and 6 display corresponding results for the 600–799 m class.

The numbers of observations in each period are small and the detailed relationships complex. Plots of probabilities derived from Figures 3 – 6 for 50 per cent falls and for 25, 50 and 100 per cent rises against lag time were drawn for 04–08 and for 20–24 h GMT starting periods for both initial visibility classes in an attempt to clarify these relationships. The plots show that the probabilities for a 50 per cent fall are greater for all time lags for starting times in the 20–24 h than in the 04–08 h period for both initial visibility classes. For the 600–799 m class this is also true for rises of 25 per cent, 50 per cent and 100 per cent. For rises from the 200–399 m initial visibility class there is a tendency for the probabilities to be similar for the morning and evening periods for lags up to 20–30 minutes and then for longer lags the probabilities become higher in the morning period than in the evening period—for which after about 20 minutes' lag the probability decreases with increasing lag.

Variations in probabilities of visibility changes with type of fog.

The 26 'occasions' were separated into radiation and advection fog types by a subjective assessment using the Central Forecasting Office hourly charts. There were only four advection 'occasions' out of the total of 26; nevertheless type (i) analyses were carried out on the advection fog subsample for all hours combined (which in practice meant 20 h through midnight to 11 h for this subsample). The results for selected time lags and initial visibility classes are compared with the results for the total sample (which of course includes the advection fogs) in Table II. This shows that in general there is a lower probability of rises and falls in visibility in a given time lag and initial visibility class in the advection subsample than in the total sample (and hence than in the radiation subsample). This finding that advection fogs are less prone to change in visibility agrees with that of Chisholm and Kruse (1974).

Diurnal variations in occurrences of poor visibilities

To investigate a diurnal variation in occurrences of poor visibilities, times when the visibility (i) was below (with a maximum of one occurrence per 'occasion'), (ii) first fell below, and (iii) first rose above 1500, 800, 400, 200 and 100 m in each of the six four-hour periods 00–04, 04–08,.... 20–24 h GMT were determined. Results are displayed in Figures 7(a)–(c). Figure 7(a) indicates that the most likely period for visibilities less than 1500 m, 800 m and 400 m to occur is 20–08 h, for 200 m, 00–04 h and for 100 m, 00–08 h. Figure 7(b) shows 20–24 h to be the most favoured time for visibilities to fall below 1500, 800 and 400 m, and 20–04 h for falls below 200 m. Figure 7(c) shows a complex distribution depending on the visibility limit considered. The low frequency of rises above all the limits for the period 12–20 h is associated with the small number of poor visibility events encountered in this period.

Conclusion

The probabilities of changes of visibility expressed as percentage changes of the initial visibility are different for rises and falls and vary with the magnitude of the initial visibility and the time lag. They also vary with time of day and with type of fog.

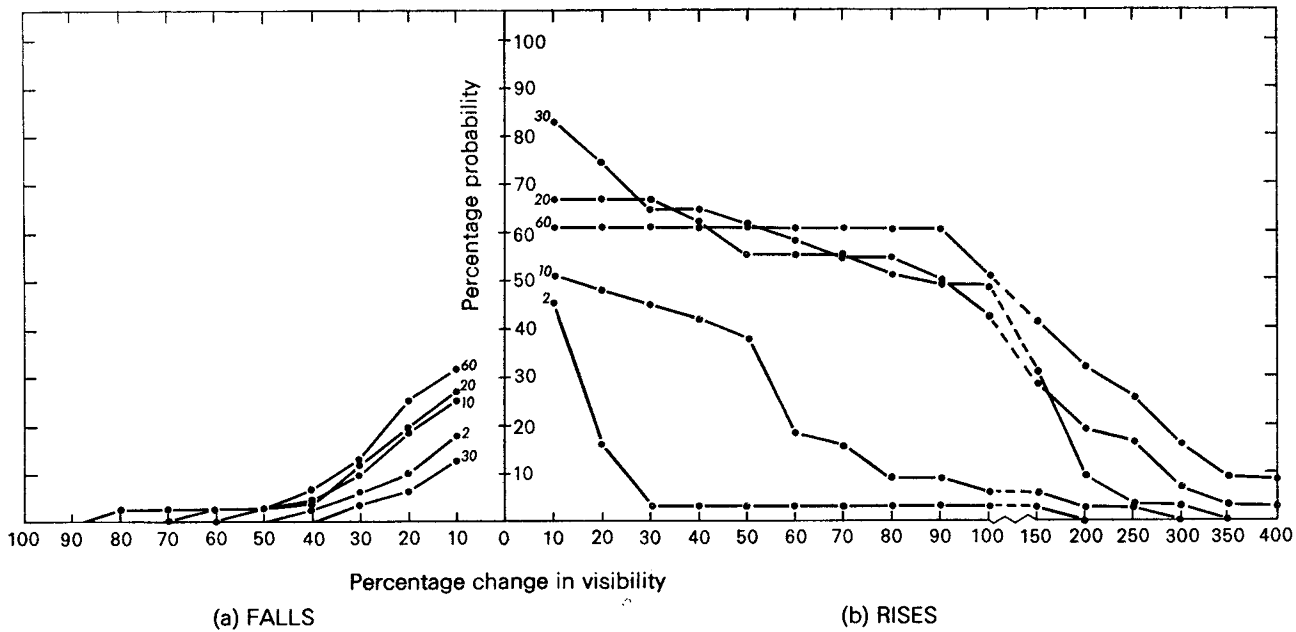


FIGURE 3—PROBABILITY THAT (a) A FALL (b) A RISE WILL OCCUR THAT EXCEEDS A GIVEN PERCENTAGE VISIBILITY CHANGE AFTER A SPECIFIED TIME LAG

Time period 04 h–08 h (starting times). Initial visibility in range 200–399 m. Average number of events: Rises 18, Falls 12. Values for lags of 60, 30, 20, 10, 2 minutes.

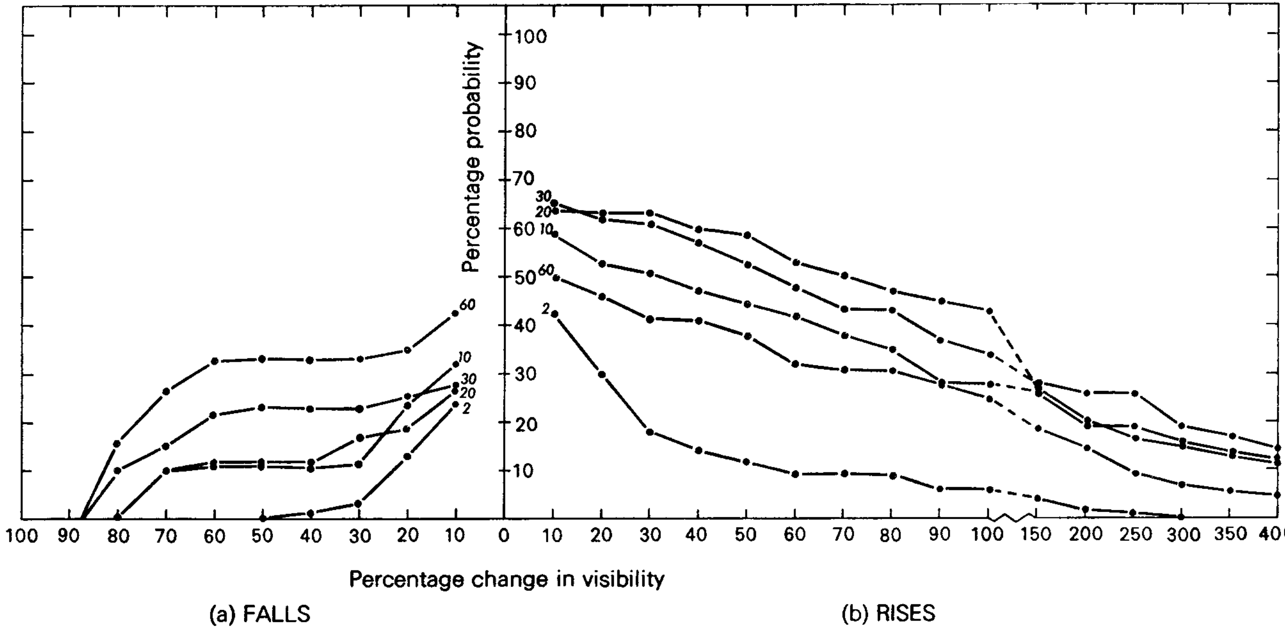


FIGURE 4—PROBABILITY THAT (a) A FALL (b) A RISE WILL OCCUR THAT EXCEEDS A GIVEN PERCENTAGE VISIBILITY CHANGE AFTER A SPECIFIED TIME LAG

Time period 20 h–24 h (starting times). Initial visibility in range 200–399 m. Average number of events: Rises 32, Falls 24. Values for lags of 60, 30, 20, 10, 2 minutes.

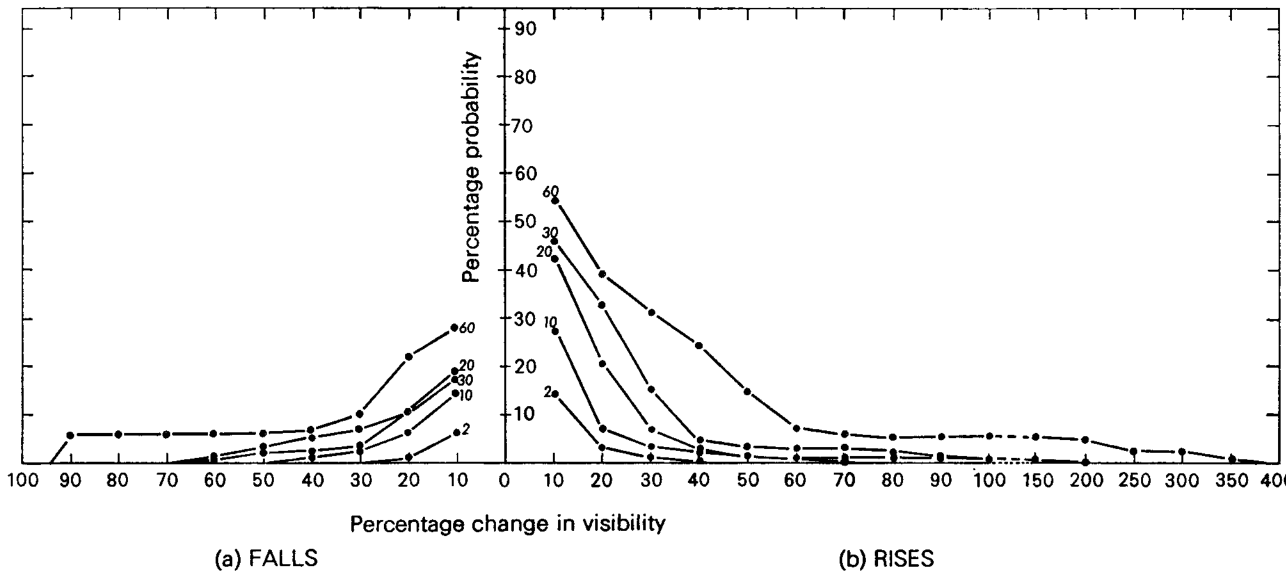


FIGURE 5—PROBABILITY THAT (a) A FALL (b) A RISE WILL OCCUR THAT EXCEEDS A GIVEN PERCENTAGE VISIBILITY CHANGE AFTER A SPECIFIED TIME LAG

Time period 04 h–08 h (starting times). Initial visibility in range 600–799 m. Average number of events: Rises 129, Falls 67. Values for lags of 60, 30, 20, 10 and 2 minutes.

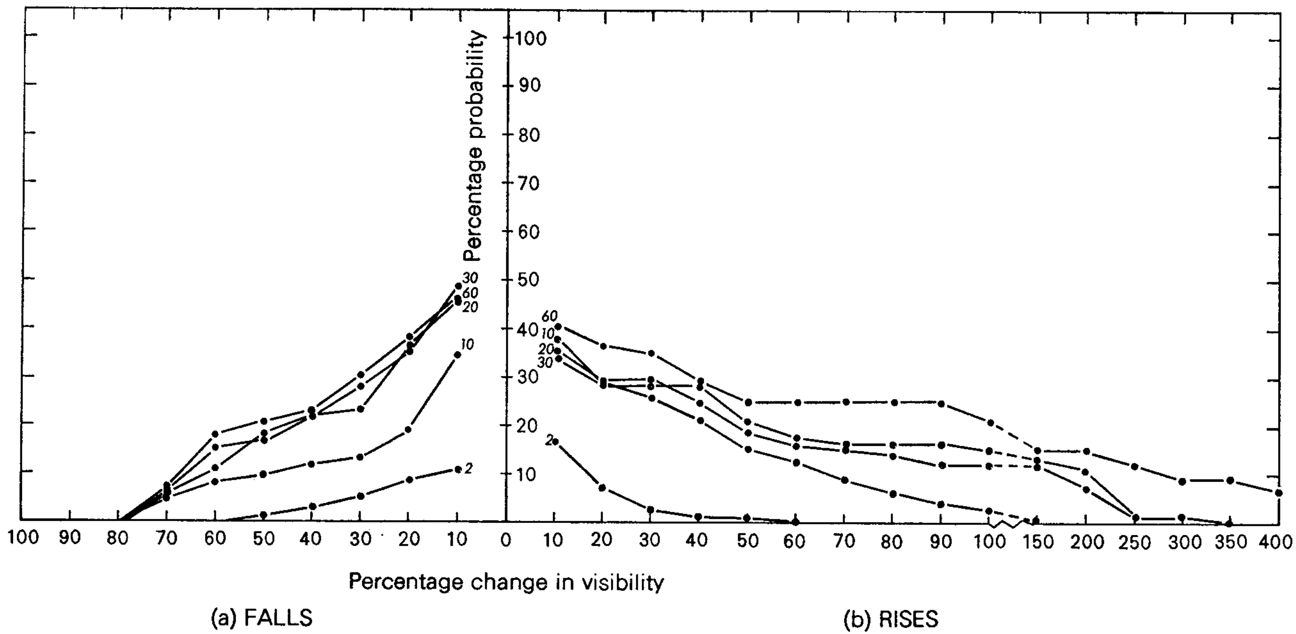


FIGURE 6—PROBABILITY THAT (a) A FALL (b) A RISE WILL OCCUR THAT EXCEEDS A GIVEN PERCENTAGE VISIBILITY CHANGE AFTER A SPECIFIED TIME LAG

Time period 20 h–24 h (starting times). Initial visibility in range 600–799 m. Average number of events: Rises 38, Falls 35. Values for lags of 60, 30, 20, 10 and 2 minutes.

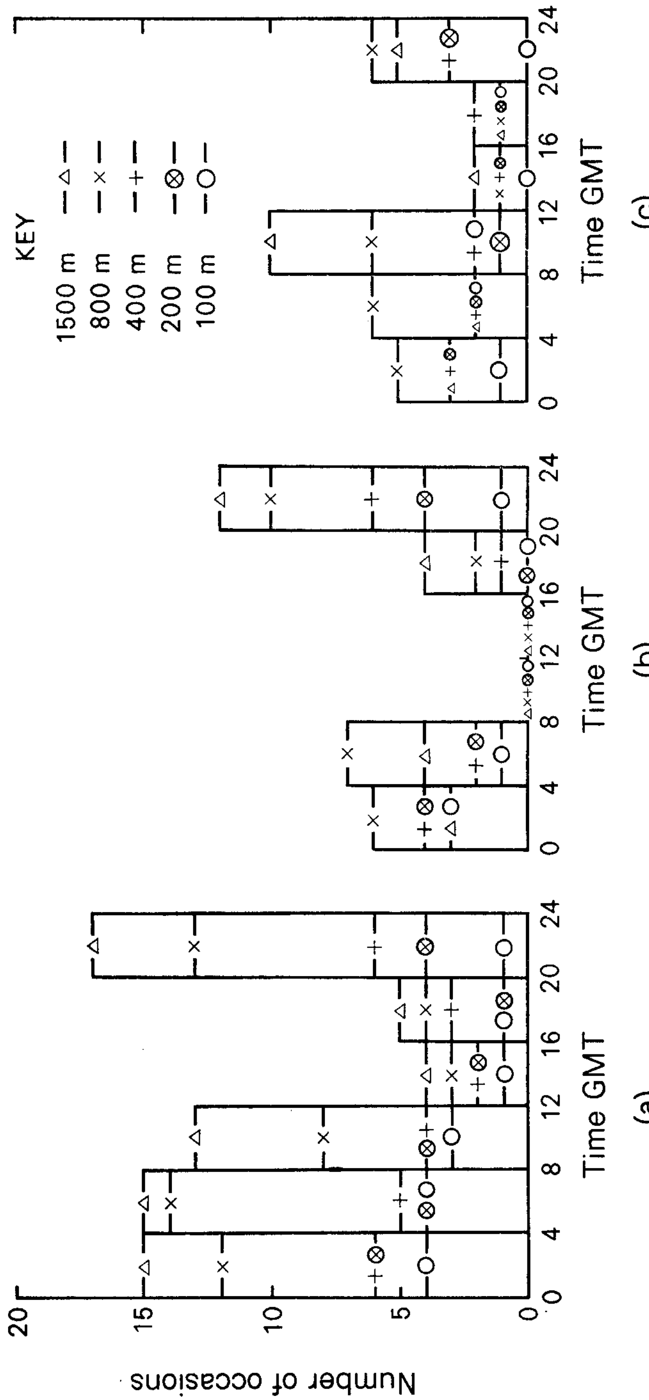


FIGURE 7—NUMBER OF OCCASIONS IN EACH TIME INTERVAL THAT THE VISIBILITY (a) OCCURRED (b) FIRST FELL BELOW (c) FIRST ROSE ABOVE, THE GIVEN VISIBILITY LIMIT

TABLE II—COMPARISON BETWEEN ADVECTION FOG AND TOTAL FOG SAMPLES. PERCENTAGE PROBABILITY OF GIVEN PERCENTAGE VISIBILITY CHANGES OCCURRING IN SPECIFIED TIMES FROM DIFFERENT INITIAL VISIBILITIES, FOR FALLS AND RISES SEPARATELY

Time lag	Initial vis.	Fall (F) or Rise (R)	Total (t) or Advection (a) sample	No. of obs.	Percentage visibility change										
minutes	*metres*				20	40	60	80	100	150	200	250	300	350	400
	200–399	F	t	94	23·4	3·2									
			a	10	10·0										
2		R	t	118	39·8	16·9	12·7	9·3	7·6	5·1					
			a	13	23·1										
	600–799	F	t	238	7·1	2·1									
			a	38	2·6										
		R	t	233	8·6	4·2									
			a	42											
	200–399	F	t	84	36·9	15·5	7·1	1·2							
			a	9	22·2										
10		R	t	132	78·8	66·7	53·0	44·7	31·8	19·7	12·1	7·6	6·1	5·3	3·0
			a	15	80·0	66·7	33·3	13·3							
	600–799	F	t	201	23·4	11·4	5·0	1·5							
			a	38	15·8	5·3									
		R	t	275	27·3	10·9	7·3	4·7	1·8	0·4	0·4	0·4			
			a	45	22·2	11·1	8·9	6·7							
	200–399	F	t	74	54·1	36·5	29·7	14·9							
			a	3	33·3										
30		R	t	142	91·5	78·9	69·7	62·0	54·9	43·0	30·3	23·2	18·3	14·8	13·4
			a	21	80·9	66·7	57·1	52·4	33·3	14·3	9·5	9·5			
	600–799	F	t	188	43·1	22·3	9·0	4·3							
			a	24	37·5	25·0									
		R	t	289	56·4	27·3	16·3	12·8	9·7	6·6	3·1	1·4	1·0	0·7	0·3
			a	59	30·5	18·6	18·6	15·3	10·2	5·1	5·1				

Blanks denote zeros.

For the 24 hours considered together, in general the lower the initial visibility and the longer the time lag the greater the probability of a change exceeding specified percentage rises and percentage falls. The probabilities of specified percentage changes are usually larger for rises than for falls, but this is largely due to there being lower limits to the possible percentage falls which can be observed. Percentage changes in visibility with increasing lag times for restricted periods of the 24 hours are more complex. In particular for rises in the 200–399 m initial visibility range in the period from 20 h to midnight, probable percentage changes in 60 minutes are less than those in 30 minutes and even in 10 minutes.

Percentage changes of visibility with time are less in advection fogs than in the more common radiation fogs.

ACKNOWLEDGEMENTS

I should like to thank the Transport and Road Research Laboratory and Mr H. A. Douglas (Meteorological Office) for making available the data used in this study, and Mr P. F. Lavington, who carried out programming for the work on diurnal variations in probabilities of visibility changes. I am also greatly indebted to Mr C. L. Hawson for his help and advice.

REFERENCES

BRIGGS, J. 1969 Visibility variations at London/Heathrow Airport. *Met Mag*, **98**, pp. 135–139.

CHISHOLM, D. A. and KRUSE, H. 1974 The variability of airport visibility: a preliminary assessment. Air Force Cambridge Res Lab, *Environ Res Pap* No. 462, Bedford, Mass.

LE GRICE, SARAH K. 1974 A preliminary assessment of the variability of visibility with time during periods of low visibility near a motorway. (Unpublished, copy available in Special Investigations Branch, Meteorological Office, Bracknell.)

551.593.653 : 77

HIGH-RESOLUTION CINE AND TELEVISION OBSERVATIONS OF NOCTILUCENT CLOUDS

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SUMMARY

An account is given of high-resolution cine and television observations of noctilucent clouds (NLC) made from Aberdeen in 1976 and 1977. The merits of the two methods are compared with each other and with other methods including stereoscopic phototheodolite observations. It is concluded that there remains much useful work which can be done with apparatus similar to that which was used at Aberdeen, and that the best recording medium for such observations is black and white cine film.

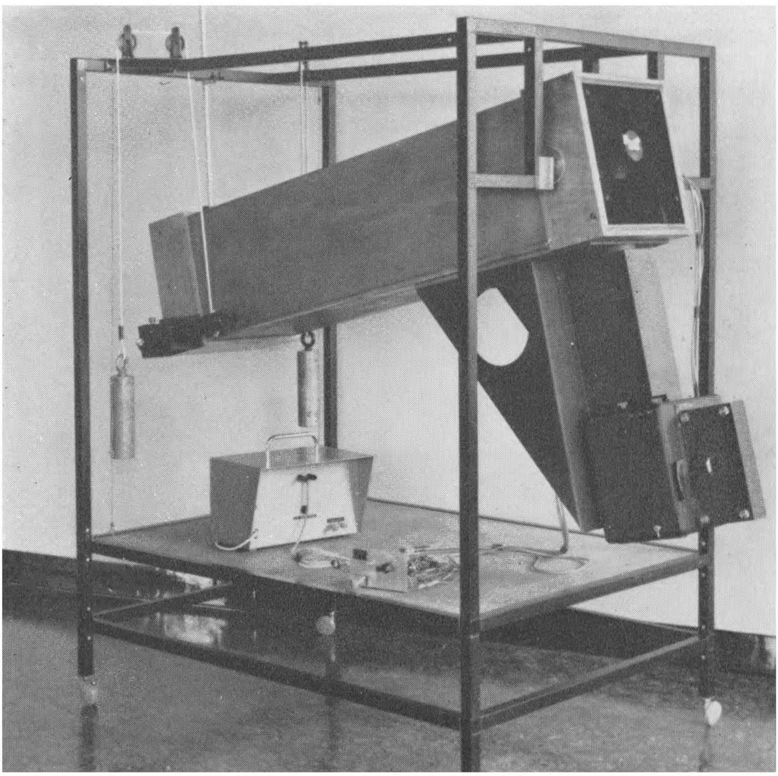

PLATE I—APPARATUS FOR HIGH-RESOLUTION CINE PHOTOGRAPHY OF NOCTILUCENT CLOUDS

PLATE II—ONE FRAME OF A CINE FILM OF NOCTILUCENT CLOUDS

Taken at 0050 UT on 21 July 1976 from Aberdeen. Exposure 19 s. Azimuth 027°, elevation 5·43°.

PLATE III—FIELD OF VIEW OF PLATE II

Note the twin spires of St Machar's Cathedral, Aberdeen, seen from Aberdeen University Natural Philosophy Department.

Photograph by M. Gadsden

Photograph by permission of the East Anglian Daily Times

PLATE IV—TORNADO DAMAGE AT NEWMARKET, 3 JANUARY 1978

See page 308.

To face page 305

Photograph by permission of the East Anglian Daily Times

PLATE V—TORNADO DAMAGE AT NEWMARKET, 3 JANUARY 1978

See page 308.

1. Introduction

Noctilucent clouds (NLC) are very tenuous, bluish-white clouds which occur near the mesopause, that is to say at altitudes of 80–85 km, during the summer months at high latitudes. They are most commonly observed on clear nights between 55° and 65° latitude when the sun is between about 6° and 14° below the horizon. Photographic records of NLC have been made ever since they were first observed, in 1885 (Jesse, 1890), and there is now a considerable photographic record of NLC from most parts of the world from which they have been seen (Fogle, 1966). Absolute determinations of the positions of NLC were made as early as 1887 (Jesse, 1890) by taking simultaneous photographs from two observing stations. Witt (1962) has produced the best stereoscopic photographic record to date, using a pair of phototheodolites with long focal lengths (380 mm) and recording the images upon glass plates. Witt's photographs show considerable fine detail, at scales of about one minute of arc, and give a good three-dimensional representation of NLC structure.

NLC features can be seen to move and change their form quite rapidly, and in order to record these movements it is necessary to use some kind of motion picture apparatus. Time-lapse cine films of NLC have been made on several occasions (Witt, 1964, for example) but the small film format (16 mm) and wide field of view has meant that cine films which have been produced have not had sufficient resolution to show the time development of the fine detail mentioned in the previous paragraph. In order to record the movements of such detail, a program of high-resolution motion picture observations of NLC was conducted at Aberdeen (57° 09′ N, 2° 08′ W); the methods which were used are described in the next section.

2. Apparatus and observations

The optical system which was used consisted of a Newtonian reflecting telescope with a 217 mm objective mirror of focal length 1·2 m, to which was attached a pair of photographic lenses to increase the effective aperture ratio to about *f*/2·5 (Plate I). The effective focal length was 530 mm, somewhat greater than the focal lengths of Witt's phototheodolites. Observations of NLC were made during the summer months of 1976 and 1977.

For the 1976 observations a 35 mm time-lapse cine camera was attached to the optical system, and Kodak High Speed Ektachrome film was used. About 10 m of film were successfully exposed on the night of 20/21 July 1976, with exposure times of 19 s and 8 s. Plate II is a black and white copy of one of the frames of the film, and Plate III shows the field of view in relation to a larger part of the NLC display. For the 1977 observations a Grant & Taylor GT50/NV television camera, fitted with an RCA 4804 S.I.T. tube, was used in place of the cine camera. About 30 minutes of videotape of NLC were recorded on the night of 22/23 June 1977.

3. Features of NLC which were observed

The most noticeable feature in Plate II is the billow-like structure which can be seen, particularly towards the top of the picture. On the assumption that the clouds are at 82 km altitude—all reliable NLC height determinations give heights close to this (Fogle, 1966)—the billows are from 1 to 5 km long, and have a crest to trough height of up to 1·8 km. If the billows are followed on the film, from frame to frame, they are found to grow and decay with time constants of about 100 s, and they move with speeds of up to 100 m/s, presumably following the background wind motion. The television pictures show similar features, and also show that these features appear to turn over, giving some indication of the magnitude of the background wind shear—about 0·025 s^{-1}. A more comprehensive analysis of the movements observed is given elsewhere (Jenkins, 1978).

4. Comparison of methods

The *angular resolution* of the cine system was about 20 seconds of arc, for sharp objects. This is far superior to the angular resolution in photographs taken using short-focus lenses. It is about the same as the angular resolution of Witt's apparatus—NLC features with angular dimensions down to one minute of arc were observed in each case. Because Witt used two cameras, he obtained a good representation of the three-dimensional form of such features, but this was not the case at Aberdeen. The angular resolution of the television system was poorer—about one minute of arc for sharp objects, and considerably worse for low-contrast NLC features.

The *field of view* of the Aberdeen apparatus was 2·6° × 2° for both the television and the cine systems, so that the long waves and bands which are often seen in NLC displays could not be distinguished. In this respect, Witt's photographs were far superior, having a field of view of 25° × 16°, so that both large and small NLC structure could be seen.

The *sensitivity* of the High Speed Ektachrome film emulsion was found to be adequate, at 19 s exposure, for solar depression angles of at least 12°, but the colour rendering was poor at solar depressions of more than 11·5°. The sensitivity of the television camera was adequate for the solar depression angles encountered during the display of 22/23 June 1977, but these did not, however, exceed 8·5°.

Time resolution. The development of the billow-like NLC features in time was better represented by the Aberdeen cine and TV systems than by Witt's photographs, as the features could change shape completely in the five minute intervals between successive plates exposed by Witt. The amount of blurring due to movement of the NLC during the exposure will be less, for a given light level and aperture ratio, if a faster photographic emulsion is used. High Speed Ektachrome has a rated speed of 160 ASA, but this decreases to 80–56 ASA for exposure times of 1–10 s. The effective speed of an equivalent black and white emulsion (Kodak Tri-X Pan, rated at 400 ASA) is 400–280 ASA for the same exposure times. The exposure times for the *f*/2·5 cine systems (19 s and 8 s) were comparable to those for Witt's *f*/5 phototheodolite system (25 s–5 s). The difference in aperture ratio was compensated for by the slower emulsion speed of the High Speed Ektachrome in comparison with Witt's P1200 plates which were rated at 400 ASA, so that the amount of movement of NLC features during exposure, for similar light levels, should be about the same for both methods.

Colour representation. NLC differ from the background sky not only in their brightness, but also in their colour saturation*. Colour film should therefore give a better representation of them than black and white film, but this advantage is outweighed by the lesser sensitivity of colour film.

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* *Colour saturation* is the degree to which a colour departs from white and approaches the pure colour of a spectral line.

5. Conclusion

It is worth while observing NLC with as good space and time resolution as possible, for it is the small-scale structure of NLC and the short-time-scale changes in this structure which raise the most interesting questions and enable the most definite conclusions to be drawn about conditions near the mesopause (Jenkins, 1978). For such high-resolution observations, the previous discussion shows that sensitivity, angular resolution and time resolution have to be balanced against each other. The angular resolution and contrast of cine film are better than those of television, but a time resolution of one second may be necessary to avoid blurring. It is therefore necessary to use as fast a film as possible, which means that black and white film needs to be used for the best results.

There may be considerable advantage in using a combination of an image intensifier and a cine camera; present technology is capable of producing image intensifiers with light gains of 100 and more and resolutions better than 0·02 mm over an area 100 mm in diameter (Johnson, 1972). If there is structure present in NLC smaller than one minute of arc, the use of such an image intensifier may well be essential. Alternatively one can aim to record NLC movements using apparatus with a somewhat wider field of view, in order to show the long waves and bands. Thirty-five millimetre cine film remains the better recording medium, as its angular resolution is better than that of television. It is, however, necessary that the fine detail should still be visible, as it is the fine detail that gives an indication of the background wind.

There remains, however, a considerable amount of work which can still be done with apparatus similar to that used in Aberdeen. At the present stage, the apparatus has produced good records of only two NLC displays. It would be advantageous to obtain records of the drift and development of small structures from a greater number of NLC displays, in order to obtain a more representative picture of atmospheric motions in the neighbourhood of the mesopause.

Acknowledgements

This work was done while I was in receipt of a Science Research Council research studentship. I am most grateful to Dr P. Rothwell of Southampton University for the loan of the S.I.T. television camera, and to Dr R. Eather of Boston University for the 35 mm cine camera. I also thank Drs M. Gadsden and P. Wraight for many helpful discussions and suggestions made during the course of my work.

References

FOGLE, B. 1966 Noctilucent clouds. Geophysical Institute Report UAG R-177, University of Alaska.

JENKINS, A. D. 1978 Noctilucent clouds: structure and dynamics. Ph.D. thesis, University of Aberdeen.

JESSE, O. 1890 Luminous clouds. *Nature*, **43**, pp. 59–61.

JOHNSON, C. B. 1972 A magnetically focused image intensifier employing evaporated field electrodes. *Advances in Electronics and Electron Physics*, **33**, A, pp. 93–97.

WITT, G. 1962 Height, structure and displacement of noctilucent clouds. *Tellus*, **14**, pp. 1–18.

1964 Noctilucent clouds (16 mm colour cine film). Institute of Meteorology, Stockholm University.

551.515.3

THE NEWMARKET TORNADO OF 3 JANUARY 1978

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SUMMARY

A tornado struck Newmarket (Suffolk) on the morning of 3 January 1978. Available synoptic data show this to be an example of such development at a cold front.

INTRODUCTION

Press reports of a 'freak whirlwind' and 'American type twister' describe the four-mile trail of blitz-like damage from Newmarket Heath (west of the town of Newmarket) to Ashley (south-east of the town) on the morning of 3 January 1978, at about 0915 GMT. Roofs were ripped off, windows smashed, a railway signal box moved on its foundations (and severely damaged) and a car overturned (see Plates IV and V). Personal descriptions include one of 'seeing it coming like a corkscrew, dark with thunder and hail'. The path of the tornado was estimated to be about 70 yards wide. Elsewhere in East Anglia local damage would appear to have been due to the general strong winds (with gusts to about 65 knots). The nearest meteorological office to Newmarket is at Royal Air Force Honington, about 17 miles east-north-east of the area struck by the tornado.

METEOROLOGICAL SITUATION

A well-marked cold front crossed East Anglia during the morning of 3 January 1978, moving south-east at about 40 knots after having advanced from a midnight position just north-west of Ireland. By 09 GMT this front had reached the position shown on the surface chart in Figure 1. Hourly charts (not reproduced) show that the surface cold front crossed the Newmarket area at about 0930 GMT. There was some evidence on hourly charts of a pressure trough ahead of the surface cold front similar to that described by Miles (1962) and the general character of the weather just ahead of the front was that of a line-squall. However, a detailed analysis of the possible line-squall structure and history has not been attempted. Precipitation was in a narrow belt commencing ahead of the front, the sequence of observations at Honington being as follows:

Time (GMT)	Surface wind *degrees/kn*	Dry bulb/Dew-point *degrees Celsius*	Weather
0852	220/28 gust 51	7.9/3.7	Cloudy, no precipitation
0920	270/36 gust 60	—	Heavy thunderstorm with hail
0935	270/30 gust 37	1.7/—	Thunderstorm, heavy rain
0950	260/25 gust 33	2.1/1.9	Thunder, slight rain
1015	260/27 gust 36	—	Rain ceased

A marked pressure jump of 2·9 mb was recorded at Honington at 0917 GMT followed by the surface wind veer at 0920 GMT and marked temperature drop (of 6·2 °C) at 0925 GMT (see Figure 2). Several other stations recorded surface wind changes more in accord with the hypothesis of a pressure trough or line-squall ahead of the surface cold front. Marham (Norfolk) reported successive

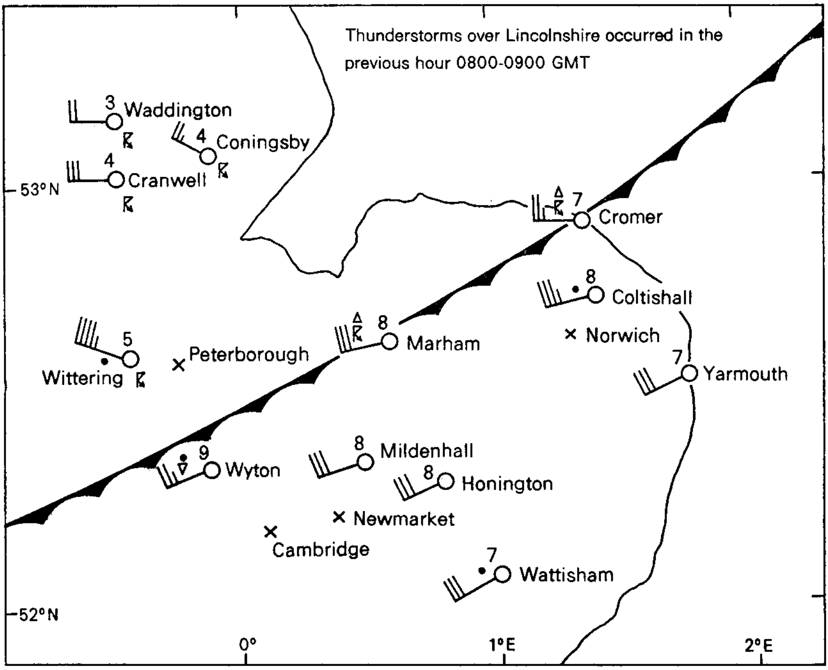

FIGURE 1—SURFACE COLD FRONT AND WEATHER AT 0900 GMT ON 3 JANUARY 1978

Note. The single figure plotted near each station circle denotes dry-bulb temperature in degrees Celsius.

hourly winds of 230°/26 kn, 250°/30 kn, and 290°/24 kn for the period 0800–1000 GMT, the pressure jump occurring about 20 minutes ahead of the surface front passage which was at 0915 GMT.

The total rainfall at Honington during the period 0920 GMT to 0950 GMT was 2·6 mm with a further 0·2 mm before the final clearance. Cloud structure ahead of the frontal zone was layer stratocumulus, altocumulus and cirrus, with rapid cumulonimbus development on the line-squall. Cloud lowered to 400 ft in the heavy rain, lifting soon after the frontal passage with breaks to well-scattered cumulus following at about 1030 GMT.

A tornado was also reported in the Hull area at 0710 GMT (just ahead of the surface cold front).

The observations and analysis are consistent with the conclusion that the tornado at Newmarket occurred on the passage of the line-squall just ahead of the surface cold front.

THE COLD FRONT

Data from the radiosonde stations shown in Figure 3 were used to construct the cross-section through the cold front which is shown in Figure 4. The full lines are wet-bulb potential temperatures and the shear zone, as determined by wind components parallel to the surface cold front, is shown by heavy dashed lines. Wind directions above the surface over East Anglia were generally between 270°

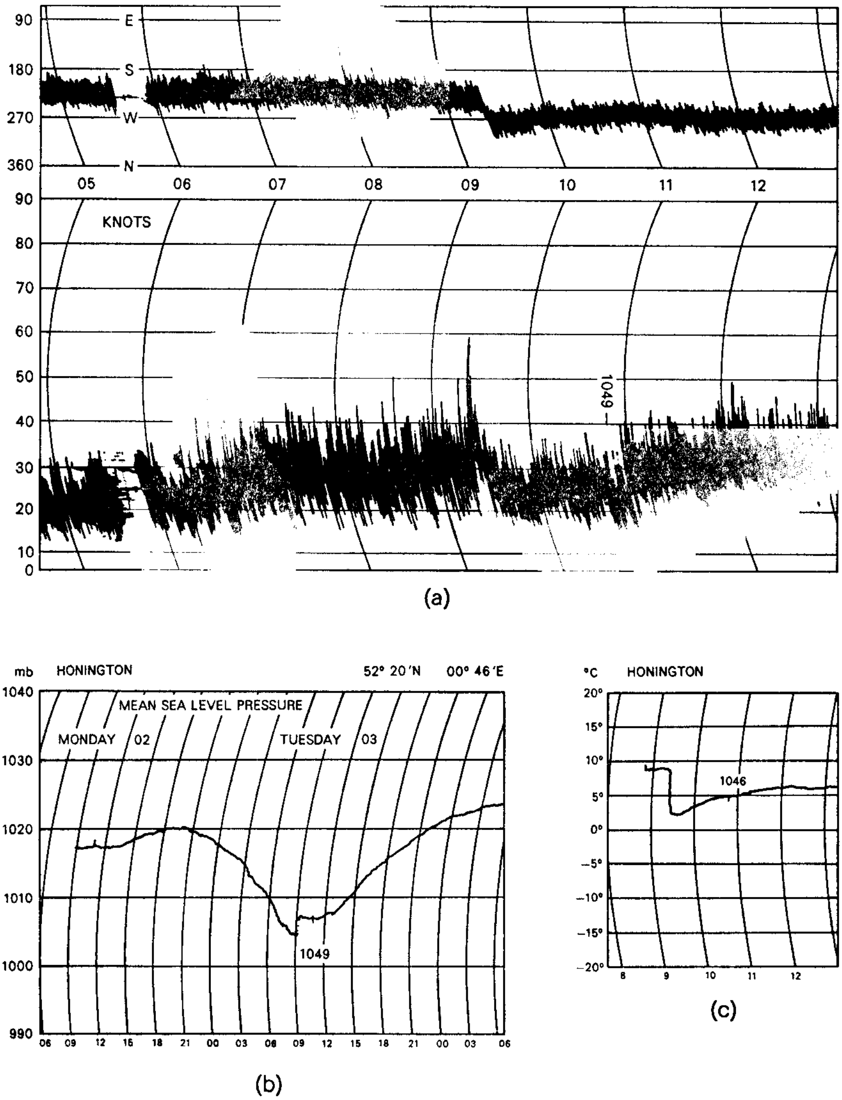

FIGURE 2—DIAGRAMMATIC REPRESENTATION OF AUTOGRAPHIC RECORDS AT HONINGTON FOR 3 JANUARY 1978

and 300° with a thermal wind directed across the surface cold front and a jet in excess of 100 kn at 300 mb (at 0600 GMT) lowering to 400 millibars by 1200 GMT. The front had the general characteristics of a kata cold front as described by Sansom (1951).

TORNADO DEVELOPMENT

The essential requirement for a tornado, as discussed by Wright (1973), is a strong persistent updraught through a deep layer—implying instability for the ascent of

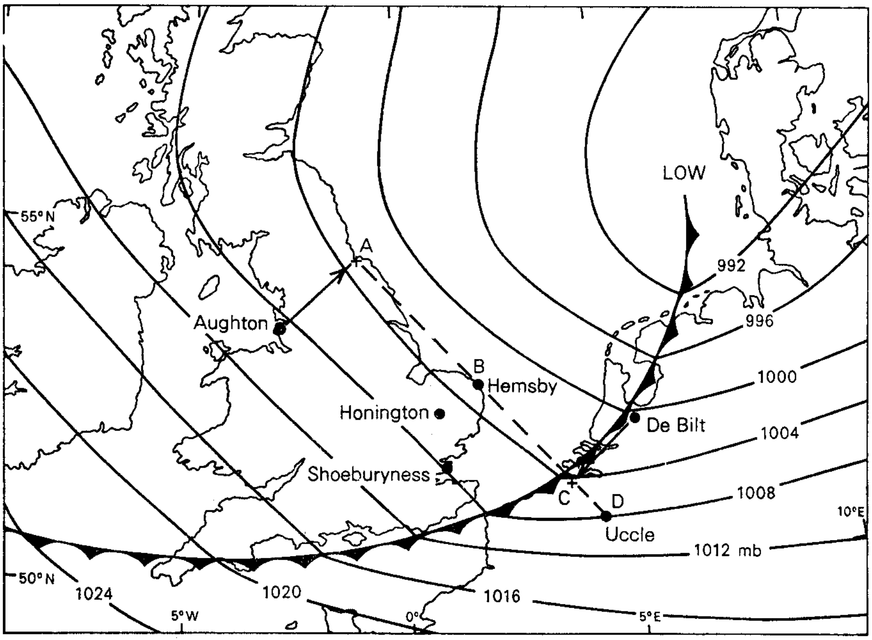

FIGURE 3—SURFACE ANALYSIS FOR 1200 GMT ON 3 JANUARY 1978

saturated air. The development is favoured if the air is potentially unstable, that is to say if there is a decrease of wet-bulb potential temperature with height. Profiles of temperature and humidity as measured by the available soundings for 3 January do not show marked potential instability; however, none of the soundings necessarily shows the precise characteristics of the air mass over Newmarket at the time of the tornado. Profiles of wet-bulb potential temperature are shown in Figure 5 which compares the Hemsby 1200 GMT data (in the post-frontal cold air) with data from a sounding carried out at Shoeburyness at 1002 GMT (air some 40 nautical miles ahead of the cold front). Honington surface observations give a surface wet-bulb potential temperature of about 6 °C just before the marked drop in temperature at 0925 GMT. If we allow for these warmer surface conditions and postulate over-running of the cold air at higher levels then a profile showing a decrease of potential wet bulb with height is obtained. Such over-running of the cold air is a common feature of kata cold fronts, as is the development of line-squall characteristics. Inspection of the cross-section in Figure 4 reveals that although no clear-cut 'cold nose' above the surface appears, some instability of this type is shown to a limited degree and the cold wedge (as defined by the wet-bulb potential lines) is very steep.

The fact that deep convection did occur with cumulonimbus cloud is evident from the actual weather observed. The marked temperature fall at Honington at 0925 GMT was probably due to heavy rain falling into unsaturated air. Wright (1973) associates one occasion of a tornado in Yorkshire with the cold downdraught of a storm on a gust front (resembling a small-scale cold front). An account by Lacy (1968) notes several tornadoes which occurred in association with the passage of a cold front.

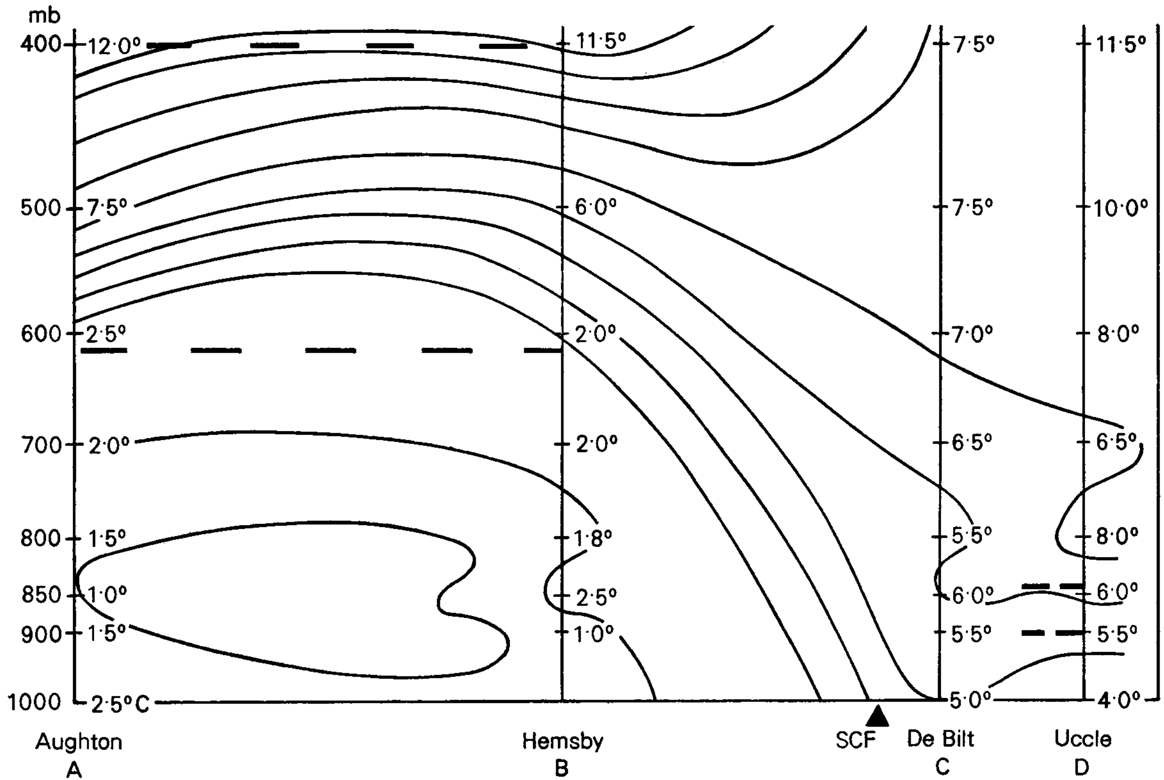

FIGURE 4—AEROLOGICAL CROSS-SECTION AT 1200 GMT ON 3 JANUARY 1978

Full lines are wet-bulb potential temperatures in degrees Celsius. Heavy dashed lines show upper and lower limits of shearing zone. SCF is surface cold front.

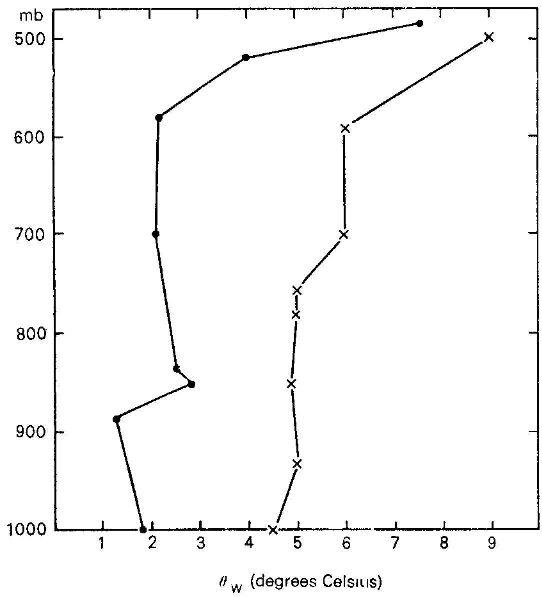

FIGURE 5—PROFILES OF WET-BULB POTENTIAL TEMPERATURE ON 3 JANUARY 1978
· —— · Hemsby 1200 GMT × —— × Shoeburyness 1002 GMT

This limited investigation only highlights the more obvious features of the meteorological situation of 3 January 1978. Whilst distressing to those who suffered the consequences, this particular case is seen to be of meteorological interest. It alerts us to the fact that tornadoes are at least as prevalent in winter as in summer (Wright, 1973), and also provides an extreme example of local marked instability and vigorous vertical motion at a kata cold front as inferred by Sansom (1951).

The only tornadoes reported on 3 January 1978 were those at Hull and Newmarket. This localized transient nature of tornado development was aptly described, nearly a century ago as 'a local accident in a very large disturbance' (Abercromby, 1887).

REFERENCES

ABERCROMBY, HON. R. 1887 Weather (A popular Exposition of the Nature of Weather Changes from Day to Day), Chapter 10.

LACY, R. E. 1968 Tornadoes in Britain during 1963–6. *Weather*, **23**, pp. 116–124.

MILES, M. K. 1962 Wind, temperature and humidity distribution at some cold fronts over SE. England. *Q J R Met Soc*, **88**, pp. 286–300.

SANSOM, H. W. 1951 A study of cold fronts over the British Isles. *Q J R Met Soc*, **77**, pp. 96–120.

WRIGHT, P. B. 1973 A tornado in South Yorkshire and other tornadoes in Britain. *Weather*, **28**, pp. 416–428.

REVIEWS

Atmospheric Aerosols (*Developments in Atmospheric Science* 7) by S. Twomey, 250 mm × 170 mm, pp. xiv + 302, *illus.* Elsevier Scientific Publishing Company, Amsterdam, The Netherlands, 1977. Price: $49.00, Dfl 120.00.

As Dr Twomey explains in the Foreword to this book, he has not set out to produce an encyclopaedia of the aerosol nor an in-depth study of any subsection. This apology is used to create an account of those parts of the subject in which the author has been a leading research worker. It is a measure of his wide contribution that the result is a substantial study of the physics of the atmospheric aerosol. The approach also has the very great advantage of providing a truly authoritative work, in which his familiarity with the subject matter is very evident.

This characteristic, indeed the whole style of the book, is set by the introductory chapter. The wide span of the atmospheric aerosol size distribution, extending from clusters of a few molecules to precipitation particles, is used to indicate the order of magnitude of various descriptive parameters such as concentration, typical lifetimes and so on. The aim of creating an early numerate 'feel' for the subject is obvious but the importance of a quantitative rather than qualitative understanding is a constantly recurring theme.

The following three chapters provide an account of methods by which new particles are formed in the atmosphere. Creation from the solid, liquid and gaseous phases are all discussed but the formation and subsequent growth of the wet aerosol in the atmosphere is singled out for particular consideration.

The flow of the book is a little uncertain here. The reader is led from a brief introduction to nucleation theory in Chapter 2 to a more thorough treatment with some duplication in Chapter 4, but must return to Chapter 3 for an account of post-nucleation growth by diffusion. Some rearrangement here would create a more logical development, particularly as the discussion of diffusional growth is somewhat out of place in a treatment of hydrodynamic forces on a single particle and an account of Brownian motion.

The next two chapters describe a number of processes which control the size distribution and concentration of aerosol in the atmosphere. Thus in Chapter 5 the physics of coagulation under the action of Brownian motion and van der Waals–London or electrical forces is discussed as a preliminary to developing the coagulation equation. Solutions to the latter are then sought in the submicrometre regime to account for the growth of a population of aerosol of different sizes. Again Twomey is at pains to let the reader see the essence of the problems by frequent use of the simple order of magnitude approach.

Chapter 6 is concerned with the physics of removal processes. Thus the role of turbulent and molecular diffusion in dry removal, nucleation, phoretic and inertial effects in cloud droplet formation and growth, and diffusive and inertial capture by precipitation are all assessed. The importance of each process as a function of aerosol is clearly explained but the order of presentation from dry to precipitation to cloud processes is again confusing and leads to the frequent turning of pages.

The half-way point of the book is reached with the various processes and properties of aerosol net production having been reviewed. The standpoint is now changed to that of the applied scientist seeking to use this information and to understand the atmospheric role of aerosol. Chapter 7 is devoted to tropospheric phenomena. Thus condensation and ice nucleation and the ensuing precipitation-forming processes are described from the viewpoint of the cloud physicist. Again Twomey's contribution to our understanding of cloud condensation nucleation results in a particularly refreshing and pragmatic approach. Unfortunately the same cannot be said of the ice nucleation section which makes no real attempt to develop an understanding of the physical mechanisms involved.

Chapter 8 is devoted to a brief and not very authoritative account of the stratospheric aerosol before the author returns to the more familiar ground of the optical effects of individual aerosol particles. Here the formal mathematical development of Rayleigh and Mie scattering is much less valuable than his shorter description of the physics of these interactions.

In Chapter 10 the concepts of absorption, scattering and extinction coefficients, developed in the earlier section, are used in conjunction with typical aerosol size distributions to describe the macroscopic effects of aerosol on the radiation field. The use of transmitted or scattered radiation to infer properties of the aerosol and the influence of aerosol on visibility and radiative transfer are all discussed. The text is particularly useful in drawing attention to the ramifications of some commonly used, but occasionally ill-founded, assumptions in this area of the subject.

The electrical properties of aerosol are reviewed in Chapter 11. The process of diffusional differential mobility charging is described and applied to cloud droplets in particular. The relationship between particulate size/concentration and atmospheric conductivity is established and its significance discussed.

Finally, the influence of aerosol on large-scale climate is explored. Feedback processes involving interactions between the radiation field and aerosols, both directly and via their effect on the microstructure of clouds, are discussed in some detail. There is much that is stimulating in this chapter.

Many readers will be disappointed with the scope of this book. Certainly there are significant gaps in the treatment. Heteromolecular condensation receives scant attention despite its importance in gas to particle conversion. No significant discussion of aerosol chemistry is provided, still less of photochemical interactions. The assessment of measurement techniques is conspicuously absent, except in the consideration of cloud condensation nuclei, and even here the field is restricted and very dated. The opportunity to develop the concept of mobility in aerosol size measurement techniques is not taken.

The standard of the diagrams, which are almost all simple line drawings, is often poor. Some are of little conceptual or quantitative value; Figures 1.2, 2.3 and 4.3 are particularly bad in this respect. As discussed above, the overall pattern of the book is occasionally confused, often obscure. There are the usual number of what appear to be proof-reading errors, of course.

Nevertheless, Twomey's treatment of the subject is at its best in those topics where he has contributed personally to their development. Therefore we should not quarrel with his decision to maximize the coverage of this in his book. In such areas, the manner in which the subject matter is presented is, with a few exceptions, clear and stimulating. Thus, the potential user must ask himself whether his interests correspond well enough with the contents described above; when they do, this book will prove to be a valuable source of information.

P. RYDER

Climatic Atlas of the Tropical Atlantic and Eastern Pacific Oceans, by Stefan Hastenrath and Peter J. Lamb. 455 mm × 230 mm, pp. xv + 97, *illus.* The University of Wisconsin Press, Wisconsin; American University Publishers Group Ltd, London, 1977. Price £11.20.

The main content of the publication is a collection of surface climatology charts for the Tropical Atlantic & East Pacific Oceans, giving fields of several meteorological variables for the various months of the year. The Atlantic Ocean within the latitude band 30°N–30°S is fully covered. Part of the East Pacific Ocean within the same latitude band is also covered but this latter region has its western boundary at 110°W and the region analysed also excludes a sector to the south-west of the Galapagos Islands. Consequently there is a substantial part of the Tropical East Pacific not covered by the atlas.

The variables analysed for each of the 12 calendar months are surface pressure, resultant wind, sea surface temperature, horizontal divergence, total cloudiness and precipitation frequency. There are also charts, for the four mid-season months, of horizontal wind steadiness, vorticity, wind stress curl, air/sea temperature difference, specific humidity and lower-level cloudiness. A short text discusses the main features of the charts and there are tabulations of standard deviations of sea surface temperature and wind. One further chart of interest shows the density of data used in the analyses.

The base period for the atlas is 1911–1970. The data source is the several million individual surface marine observations available in the Tape Deck Family 11 (TDF11) deck at the National Climatic Center, Asheville, N. Carolina. This deck is a very valuable data compilation which has been used in some other studies, in particular for the recent revisions of some volumes of the US Navy Department's *Marine Climate Atlas of the World.*

One of the main features of this current publication which distinguishes it from earlier publications is the relatively fine resolution of the analyses and the degree of detail that is present in the charts. The basic resolution of the analyses is 1° lat./long. The surface pressure fields, for example, contain irregularities which would meet with the disapproval of some analysts. However, some of these irregularities occur in areas of plentiful data and indeed in those areas where the authors are not confident of the data base they wisely leave the analyses incomplete. The derived fields of divergence are of interest. They clearly identify the convergence zone of the surface winds over the Tropical Atlantic, and the seasonal migration of the zone. The curl of the wind stress is diagnosed because of its relevance as a forcing function for oceanic motion. Negative wind stress curl calls for upwelling in the southern hemisphere and for downwelling in the northern hemisphere.

The visual presentation of the information is very good. The map projection used is a simple one; the scale of the charts is sufficient to permit detailed scrutiny although the overall dimensions of the atlas are quite small; and the latitude/longitude markings are well arranged. Each of these three considerations is important if such publications are to be of practical use.

The atlas is a welcome advance, both in data content and display format, in the documentation of tropical climatology.

D. B. SHAW

Climatic change, edited by John Gribbin. 250 mm × 190 mm, pp. xi × 280, *illus.* Cambridge University Press, London, 1978. Price £17.50 hardback; £6.50 paperback.

In the preface to this book the editor says he felt the need for a single textbook which would give him an understanding of the basics of climatic change. This remark followed mention of the droughts in the Sahel and Ethiopia, bad harvests in the USSR and so on, and one supposed that the understanding he sought was principally to help him (and others) judge the prospects of this sort of event occurring in the next few decades. This was in 1973 when Volume I of Lamb's 'Climate, Present, Past and Future' had already been published and it was known that Volume II was in preparation. Why, one wonders, did he feel the need for another textbook especially after the appearance in 1975 of 'Understanding Climatic Change' prepared for the United States National Academy of Sciences under the joint editorship of Verner Suomi and Lawrence Gates?

If he felt that the issues involved in the Sahel drought (the northward extent of the south-west monsoon of West Africa) or in the Russian droughts (the amplitude and location of the major troughs and ridges in middle latitudes) have not yet been adequately presented in a textbook one can feel sympathy with his need. These issues probably cover the borderland between the problems of long-range forecasting (1 month to a season) and the shortest scales (a few years to a decade) of climatic fluctuations and represent one of the most formidable problems in meteorology. Was he indeed aiming to illuminate this dark region?

The first three chapters of the book do not suggest he was, covering as they do climatic changes on scales of hundreds to hundreds of thousands of years. The title of Chapter 9—'Short term astronomical effects' is more encouraging but the discussion is mainly limited to events on a time-scale of a few days. The rest of the book gives little reason to think that he was aiming so high, and the book has to be judged as another general text on this over-exposed and under-developed subject of climatic change.

Twelve scientists of varying degrees of eminence have made contributions and the editor has himself written three short chapters and collaborated with Professor Lamb in a chapter I would have thought that doyen of climatic change in Britain quite capable of writing himself. What is the nature of the book that has resulted? It is a hotch-potch without any form or linking theme even though some of the ingredients are of good quality, and deserve a better recipe.

Following the opening three chapters which deal adequately with climates of the distant past, the first section closes with a chapter entitled 'Climatic change in historical times' by Gribbin and Lamb. This is a reduced version of the equivalent chapter in Lamb's Volume II but with an addition which turns out to be more in the nature of advertisement than science. I refer to the presence of the Rossby formula in the discussion of the change in spacing of surface pressure troughs between the periods 1790–1829 and 1900–39. It is reasonably pointed out that on applying this formula the increase in wavelength shown by Lamb's data is too great to be explained by changes in circulation intensity, and 'some slight change of latitude of the strongest upper westerlies must also have taken place with a poleward displacement of a few degrees of latitude'. It is a pity the quantification was not taken a stage further for I estimate that to explain the increase in this way would require a northward shift of 15–20° of latitude. With this improbability recognized perhaps the joint authors would then have asked themselves whether the data were erroneous or the Rossby formula inapplicable and we might have been spared a piece of pseudo-science.

The next chapter 'The heat balance of the Earth' is written by Budyko, the celebrated Russian climatologist, and contains material that has appeared in *Tellus* and a Leningrad journal: it reflects no credit on the supervision of the Editor. There are too many typographical errors (p. 98 has two very irritating mistakes) and all references to Soviet publications have been left in Cyrillic script which shows the erudition of the printers but does nothing for the reader. The end of this chapter where Budyko concludes that the atmospheric transparency stopped falling in the middle of the 1960s and that the warming due to the increase of CO_2 has now taken over and will continue, perfectly illustrates the kind of madness that seems to infect workers in this field when they move from analysis to prediction.

Chapter 6—'Recent changes in snow and ice'—has been written from a very narrow viewpoint: the influence of snow and ice on climate change is treated as a primary rather than a feedback effect. The differences in the change of total snow and ice cover between winter and summer for the two hemispheres, which are surely mainly due to their different thermal capacity, is presented in a graph ostensibly showing the important part played by the extent of snow and ice in the different climates of the northern and southern hemispheres.

Section 4—'Modelling the changing climate'—opens with a diffuse chapter on the role of the oceans and continues with one on the use of numerical models in studying climate change. This and the next chapter on the interpretation of results from numerical models illustrate how far there is yet to go in this potentially very important art.

The book concludes with a section entitled 'Climate and Man'. Kellogg in a carefully reasoned chapter examines the effect of man-made changes in the constitution of the atmosphere on temperature and concludes that the so-called 'anthropogenic' aerosols may not have stopped increasing as Budyko says. More important, he argues that we cannot be at all certain what their effect has been on northern hemisphere temperature during these last three decades. Schneider, known through his book 'The Genesis Strategy' for his passionate concern that governments should act to insure against the direct effects of climatically induced crop failures, and Temkin, also from the National Center for Atmospheric Research in Boulder, Colorado, USA, co-operate to describe the effect of climate on man.

Professor Flohn contributes an interesting appendix most of which, however, like Chapter I and II, has little relevance to events on a time-scale of a few years.

This is a nicely produced book, as you might expect from the Cambridge University Press, but assuming they wanted to have a text on this subject on the market it says little for their judgement that they entrusted its editing to an astrophysicist: the tough problems in this field, apart from those concerning variations in the Solar Constant, are meteorological not astrophysical.

M. K. MILES

NOTES AND NEWS

Retirement of Mr E. J. Sumner

Mr E. J. Sumner, Assistant Director (Systems Development), retired from the Meteorological Office on 5 June 1978 after a career of over 36 years.

Having graduated with honours in mathematics at Oxford, Eric Sumner joined the Office in 1941 and was soon involved in forecasting at RAF stations. He held a commission as a Flying Officer in the RAFVR from 1943 to 1946, at which time he was demobilized and took up civilian duties as a Senior Scientific Officer. After a short spell in climatology at Harrow, he joined the newly formed Forecasting Research Branch at Dunstable in 1948. His papers on vertical stability in synoptic development, and on blocking, are still worth consulting some 25 years later. In 1953, he moved to the Central Forecasting Office where he proved his skills as a forecaster and shrewd synoptician.

He was promoted to Principal Scientific Officer in 1958 at a time when the Office was acquiring its first electronic computer (METEOR) for research into numerical weather forecasting. It was not long before the possibilities of using computers for automatic data processing were realized, both by research workers and by those engaged in developing climatological services. Mr Sumner was given charge of the data processing section of the newly formed Support Services Branch, and moved with it to Bracknell in 1961. Shortly afterwards the Branch took over responsibility for the operation of METEOR, and was able to plan the provision of an integrated service of computing and data processing to meet the coming explosion in demand. In a review article in 1960, Mr Sumner provided a penetrating and far-sighted analysis of the dramatic developments which were to occur in the fields of meteorological computing and automatic data processing.

Throughout the Sixties, he was to be at the forefront of the rapidly changing technology of electronic computing devices. In 1964 the data processing section became a Branch, with added responsibilities for the storage of climatological data and for the development of automatic line drawing and plotting. The introduction of operational numerical forecasting with tight time schedules, following the acquisition of the KDF-9 computer in 1965, ushered in the present frenetic era of real-time computing and underlined the need for highly professional computer management. Against such a background of change, it is noteworthy that Mr Sumner was able to look so far ahead with such vision, though sometimes setting aside the practical problems of the present in his eagerness to reach out for the solutions of the future. His forthright advocacy of new possibilities has enlivened many an otherwise dull meeting.

With the introduction of computer-based systems into meteorological telecommunications, and with the need for these to be linked both to the data-processing computers and to automated outstations, a new Deputy Directorate was created in 1971 comprising Data Processing, Telecommunications and Systems Development Branches. It is never easy to establish a completely new branch, but Mr Sumner applied himself to this task with characteristic enthusiasm. Under his leadership, readily retrievable and machinable data archives were established, methods were developed for transcribing field data into computer-assimilable form, certain functions of the Library were automated, it became possible to manipulate satellite imagery by computer techniques and the basic design features of automated outstations were determined.

As is not uncommon amongst mathematicians, Eric Sumner derives much pleasure from music and is a pianist of some accomplishment. More recently his early efforts with brush and canvas have shown much promise. We wish him and Mrs Sumner a long and happy retirement in their new home in Shropshire.

M. J. BLACKWELL

International Conference on Climate and History at the University of East Anglia

The University of East Anglia are proposing to hold an international conference on climate and history on 8–14 July 1979 with contributions by climatologists, historians and archaeologists. It is hoped that workers in all three fields will be able to inform each other of the present state of knowledge of the climatological record and of the impact of climate and climatic change on past and present societies, that areas of potentially useful co-operation will be identified, and that contacts between individuals will be set up.

The conference is being planned to include sessions on the following topics:

(1) The illustration of methods used by each discipline and the increasing opportunities of using various kinds of 'fossil' records (such as tree-rings, varves, isotope studies and so on) combined with historical materials.

(2) General reviews of the conclusions so far reached in fields of common interest to climatologists, historians and archaeologists.

(3) Further discussions of (i) climate in prehistory; (ii) climate in the documented past; (iii) the past, present and possible future significance of the interrelation between climate and human activities; (iv) the implications of climatic change for the development and history of agriculture, fisheries, exploration, human health and demography, economic development, times of unrest etc.

The proceedings will include papers that discuss these matters in relation to specific problems, periods and parts of the world.

Potential participants should contact:

The Conference Secretary (Climatic and History Conference)
Climatic Research Unit,
School of Environmental Sciences.
University of East Anglia,
Norwich NR4 7TJ,
England,

as soon as possible.

THE METEOROLOGICAL MAGAZINE

NO. 1275 OCTOBER 1978 VOL. 107

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NOTICES

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Issues in Microfiche starting with Volume 58 may be obtained from Johnson Associates Inc., P.O. Box 1017, Greenwich, Conn. 06830, U.S.A.

Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1 monthly **Annual subscription £13.14 including postage**

Dd. 595890 K15 10/78

ISBN 0 11 724804 5
ISSN 0026–1149

Met.O.915
METEOROLOGICAL OFFICE

the meteorological magazine

NOVEMBER 1978 No 1276 Vol 107
Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.915

THE METEOROLOGICAL MAGAZINE

No. 1276, November 1978, Vol. 107

551.509.58:359

FORECASTING FOR THE ESCAPE OF SCHARNHORST AND GNEISENAU

By the late DR WALTHER STÖBE

An earlier English version of this article was discovered in 1975 in the Meteorological Office, RAF, Laarbruch, Federal Republic of Germany by the then Senior Meteorological Officer (Mr T. E. Williams) while he was looking through some old files; it was subsequently passed to the Defence Services Branch of the Meteorological Office at Bracknell by the then Chief Meteorological Officer, RAF Germany (Mr W. G. Durbin), and thence to the Editor of the *Meteorological Magazine*. We attempted to get in touch with Dr Stöbe at his retirement address in Munich, but were informed in reply by Frau Marie Stöbe that her husband had died in 1971. However, Frau Stöbe very kindly made available to us the original German text of the article, and also granted us permission to publish an English translation.

The original text makes reference in several places to various illustrations and figures which unfortunately are no longer available; the artwork in this present version has been devised by the Editor.

We think that all meteorologists, especially those with experience of war-time forecasting, will find Dr Stöbe's account of the difficulties faced by German forecasters of great interest and fascination; it seems to us to be a valuable addition to the already extensive literature dealing with the Second World War.

In the present translation the word 'Luftwaffe' has been retained when it stands for the German Air Force, but expressions such as 'die englische Luftwaffe' have been translated as 'the Royal Air Force'; the 'Navy' means the German Navy as distinct from the Royal Navy of Britain. The German typescript contains several underlined passages which have been rendered into italics. 'England' and 'englisch' have been rendered by 'Britain' and 'British' where appropriate.

PREFACE

No other event of the last World War can better bring home the connection between a military action and meteorological support than 'Donnerkeil', the code-name given to the break-through of the German pocket battleships through the English Channel. Firstly, it was a completely self-contained act of war and, secondly, because the Navy and Luftwaffe were working in co-operation, the meteorological setting assumed particular importance.

This paper was made possible because I, as Chief Meteorological Officer of Air Fleet 3, was responsible, with Dr Süssenberger, the Meteorologist of the Naval Group (West), for the meteorological advice and can recount the events from personal experience. In addition I had assembled a large part of the meteorological data, intending to prepare a paper later, and I kept it together during the confusion at the end of the war.

The centre of interest of the paper certainly lies in the weather situation but, despite this, the course of the escape must be described so as to complete the picture. This is an account of almost documentary fidelity, and for this I am indebted to the kindness of various people who took part in the action. Above all I must mention General Max Ibel, who furnished me with an actual account of the Air Force activity and the daily log of Operation 'Donnerkeil' up to its completion, and who was attached as Commander of the Fighter Squadrons to the Naval Commander, Admiral Ciliax. Furthermore General Koller (Rtd), who was then Chief of Staff to Field Marshal Sperrle's Air Fleet helped me considerably by drawing on his exceptional memory.

This paper ought, thus, not only to show the difficulties of the German Weather Service due to the War, but also to demonstrate that careful use of a few observations can produce effective results if ordinary ability is supplemented with a little luck.

Preparations for the operation

On 4 February 1942 I received an order from the Chief of Staff of Air Fleet 3, which was stationed in Paris, to prepare a most detailed weather forecast for the period 5–14 February 1942 as an operation was being planned to take place during this period in the English Channel. The Navy was also to take part, but I had not yet received more exact information on the type and execution of the operation.

Once again the usual difficult conditions for the advisory meteorologist were apparent. He had to be responsible for preparing a forecast for an important undertaking, but would either be given an incomplete idea of the operation or be informed at the last moment so that secrecy would not be endangered. Only a few discerning military officers realized during the course of the war that the meteorologist, who in all the important decisions in a modern war may be able to turn the scales, can never correctly prepare his forecast if he is not informed of the tactical plan in time. The opinion held by many young officers of the General Staff that the meteorologist should give only a general forecast so that the officer could make the tactical interpretation always led to failure because the officer himself could never find his own way through the vagaries of the weather, particularly under difficult war-time conditions, whereas the tactical matters were always much clearer and simpler, and the meteorologist was capable, with comparative ease, of thinking correctly on tactical matters and acting accordingly.

In addition to this major general difficulty which arose out of the need for security, another unpleasant one came along; the demand was made for a long-range forecast. The situation was that the higher the rank of the staff officer the longer ahead he had to plan, and he thus naturally demanded the same of his meteorologists in connection with the weather. However, apart from their greater experience, for the higher staff always used older meteorologists, the latter had no scientific advantage over the run-of-the-mill meteorologists. The meteorologist in the higher staff thus found it his most difficult problem to convince his military taskmasters of the limits of meteorological knowledge and capability, particularly concerning how soon one reached one's wits' end with regard to long-range forecasting.

With its scientific impossibility in mind, I at first refused to make the required long-range forecast. Only after the Chief of Staff, who always understood the difficulties facing a meteorologist, had assured me that, far from nailing the Weather Service down over any particular forecast he merely required from us the best outline we were capable of producing, did I, after consultation with my able colleague Dr Nestle, set about the venture—and that with very mixed feelings.

It must be remembered that under war conditions every ordinary forecast was already very difficult. Certainly over the greater part of continental Europe many observations were available for consideration, but for the vast expanse of the Atlantic Ocean we had nothing. Iceland had gone by the middle of June 1940 and decoding of the English or American reports was successful only on isolated occasions, so that for the western region we were dependent almost entirely on the meteorological flights.

There were four regular daily flights:

(1) From Stavanger due west to about 12°W.

(2) From Wilhelmshafen almost to the latitude of the Shetlands.

(3) From Paris into St George's Channel and the Irish Sea.

(4) From Brest north-westwards to the latitude of central Ireland.

The flights took place only once a day, so that 24 hours elapsed between successive observations, and they merely provided a scanty replacement for the usual extensive observations of normal times. The important gap constituted by Ireland* and the zone some 500 km wide between Ireland and Scotland not reached by the flights was never stopped. Isolated reports from England and Ireland, partly intercepted weather reports from airfields and partly agents' reports, were very important but throughout were quite insufficient. Thus it was quite impossible for the forecasting officer to form even a moderately accurate picture of the situation in the area of main activity over Iceland or in the East Atlantic. In practice this meant that one was never free from surprises. So the daily forecast for the battle area of Great Britain became a nerve-racking affair for every advisory forecaster in western districts. And now, to cap it all, a long-range forecast! Even in normal times this sort of practice was a tricky affair. Genuine aids were slight. The monthly forecasts from the Long Range Research Institute in Homburg were useless for advice purposes as they were too general. Forecasts of the average cloud cover or the average pressure distribution were no use. Just as little use to us was the large-scale Navy publication 'The ten main weather types over central Europe in relation to the weather in the English Channel' which had appeared in 1941. What good was it to know, for instance, that in February the frequency of weather type 7 (north-westerly weather) was 54 per cent, and that for this type Calais would have a mean temperature of 4·2 °C, while visibility would be fair or changeable? The actual weather can never be approached through such statistical means and frequencies as these. The possibility of working with symmetry points and 'mirror' curves failed because pressure data in the areas in question were either not available or were uncertain. A more valuable work, for the practical forecaster, was the article, unfortunately classified as SECRET, by the recently deceased Walter Lay called 'Synoptic pressure singularities' published in 1941 by the Reichsamt für Wetterdienst, Berlin. Here an attempt was made to construct on a seasonal basis a series of charts representing the general weather situations. A definite help in the same direction (i.e. using singularities) was the graphical presentation of the daily

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* The German reads 'Island' i.e. Iceland, which must be a typing error.

storm frequencies based on 40 year averages (after an English work covering north-west Ireland and south-east England). Unfortunately, moreover, the need for strict security ruled out any closer co-operation with the Central Weather Group at Luftwaffe HQ in Berlin, who were much concerned with long-range forecasting.

The meteorological office of the Air Fleet in Paris was therefore quite alone in this assignment. In practice the Staff was provided with long-range forecasts as follows. The starting point was the weather situation at 0800 hours on 5 February, from which extrapolation was carried out in accordance with weather developments, which corresponded roughly to Lay's charts for 7 and 12 February. From the 6th a daily correction was made to the forecast by referring to the new weather situation. In this way we groped slowly forward to a forecast for the middle of the month.

The first forecast for 5 February, which was to stretch to 14 February, shows very clearly that we knew little of what we were about, so that it was necessarily confined to generalities. The following, taken from my notes, describes how the forecast was placed before the staff officers (with the accompaniment, naturally, of verbal explanation of the appropriate weather chart).

THE PROBABLE WEATHER SITUATION IN THE BASE AREA, HOLLAND–FRANCE, 5–14 FEBRUARY 1942

'The development of the weather in the area in question will be determined by the very pronounced high-pressure area over the continent on the one hand, and advancing disturbances from the Atlantic on the other. The anticyclone over central Europe and in the east is very stable, being strengthened by the thick snow cover, and will not be broken down easily. The Atlantic disturbances coming from the north-west and west will hardly be able to reach further than Holland, whilst the cold air from the east will just about reach the Paris area.

In particular one can forecast the changes of the weather in Holland and in the coastal areas of France as follows:

5–7 February. Continuing frosty weather in Holland with occasional light snowfall and lifted fog at 600–1000 ft at times. In France a disturbance will again move further south-east or east-south-east accompanied by slight precipitation (rain) and more extensive and often complete cloud cover.

8–11 February. Holland will again lie in the frontal zone and decidedly bad weather with rain and also snow can be counted on. Later the front will move eastwards.

Changeable weather is expected in France.'

So much for the forecast, which shows that we are dealing, first and foremost, with the oscillation of a meridionally aligned trough between the continental and Atlantic highs.

As far as the general weather situation is concerned, it may be said that in consequence of the Azores High being displaced far to the north, the tracks of the Atlantic depressions lay very far north, and the continental influence had become very marked in the west, so that, according to a report in *The Times* dated 13 March 1942, February 1942 was the coldest February in England and Wales since 1895, colder in fact than the hard Februarys of 1917 and 1929.

The supplementary information for 6 February now allows a definite outlook to be given, which to some extent agrees with the actual course of the weather on 12 February.

'Sometime after 10 February the passage of individual depressions from the north-west along the east side of the intensifying anticyclone west of the British Isles is expected, so that in two to three days a pronounced bad-weather zone is expected in the region of the North Sea and the southern part of the east coast of England.'

In addition there was discussion concerning a steering from the north-west which, although not recognizable on the surface chart, had been forecast over the low-pressure areas over Norway and Russia present on Lay's charts. *The discussion of the weather situation from 7–12 February in Lay's work points to a special development of the northern source of depressions in the region of Iceland, caused by the warm air mass from the Atlantic meeting the cold Arctic air mass which was being steered southwards.*

In the meantime I had been able to gain more information about the imminent operation by illicit means. Officially, I knew only that the Luftwaffe was to protect the escape of our warships through the English Channel, and even then they gave me the wrong direction (escape from east to west). Now I was told of the weather requirements.

(1) The *ideal* weather was considered to be a situation which would prevent the much-feared British torpedo-carrying planes, and, if possible, also the bombers, from being used. This meant that very low unbroken cloud, or, even better, persistent fog, must cover south-east England.

(2) Otherwise, the Luftwaffe, meaning their fighter planes, which were very sensitive to bad weather (as they could not fly blind), must be able to land and take off unhindered and protect the ships from the British attacking aircraft without encountering weather obstacles. This meant, at best, cloudless weather with good visibility both over the North Sea and in the Channel as well as over the airfields in northern France and Belgium.

(3) In no case must the weather situation be such that the Royal Air Force could go into action, while the German aircraft could neither take off nor land, thus leaving the German ships unprotected. It was thus imperative that the weather situation should not be composed of perfect flying conditions over south-east England, with perhaps a slight cloud cover in the Channel, while the coast of France and Belgium lay under fog or deep cloud accompanied by bad visibility.

The weather conditions which the Navy demanded for the progress of the action were the following:

(1) No fog over the whole distance so that maximum speed could be used.

(2) Sea slight (because the various ships in particular the speed launches—'Schnellboote'—which protected the flanks, would otherwise be unusable).

(3) A following wind if possible.

(4) In order to make proper use of darkness the action had been timed for the days around the date of the new moon. About six days were available to choose from, namely 11–17 February, any later month than February being out of the question owing to the shorter length of the night.

It will be seen how many conditions one had to bear in mind and for the meteorologists it was a question of nerve-racking watchfulness in order not to miss any favourable opportunity and also to appreciate every unfavourable weather situation quickly so that from the beginning the prospect of success was not endangered.

Naturally the meteorologists were concerned to find all aids which were in any way available, in order to fulfil this difficult task. For the Luftwaffe there was no other possibility than to strengthen the weather reconnaissance flights. The Navy had, however, on the suggestion of Dr Süssenberger, who had been let fully into the secret earlier than I, set aside three U-boats exclusively as weather observers. They were to be placed so that not only could they watch the region of the east Atlantic High, which was the key point of our long-range forecast, but also the crucial region around Iceland. *From 8 February these reports were to be given three times daily and they meant not only an easing of the problem of the briefings, but, as further events showed, were the key to success.*

Naturally, steps were also taken to augment the few reports from our agents in Britain and Ireland, and above all to pay greater attention to the openly radioed weather messages of the Royal Air Force. The latter were certainly a welcome supplement, but were meagre both in number and value.

The supplementary forecast for 7 February showed considerable uncertainty. Over the southern North Sea a weak ridge of high pressure had built up from the west; it extended almost to the continental anticyclone over Russia. The uncertainty arose from the fact that no reports from the eastern Atlantic were to hand, and it could be assumed that, because of the south-easterly thrust, the whole Atlantic anticyclone had moved southwards, thus bringing about a simple west–east arrangement of isobars over Great Britain and the North Sea that would create a westerly weather situation which would quite upset our view of the future general situation. Besides, it could perhaps happen that because of the approaching anticyclone, widespread fog and lifted fog would occur over the Channel. A further uncertainty arose out of the impending change in the general situation in the north, as the continental anticyclone in the east appeared to be declining, and the low over Norway which was expected from Lay's analysis appeared to be forming.

So the forecast for 7 February closed with these words: 'Consequent upon the beginning of a transformation of the general weather situation (break-up of the continental anticyclone and the south-westerly movement of the Atlantic anticyclone) the further development of the general situation can be seen only with great uncertainty'.

On 8 February it was, however, already clearly seen that the ridge of high pressure which had pushed forward on the previous day would be broken down again. The reports from U-boats in the Atlantic, which were now coming in, also showed that the Atlantic anticyclone had not altered its position. Unfortunately the reports from the region of Iceland were still uncertain, but the activity of the developing low over northern Norway, which was already noticeable at high levels, had already been allowed for in the forecasts.

'The ridge of high pressure will be gradually broken down, so that the disturbances coming from the north and north-west are expected to reach the area of Holland around 9–10 February and later on 10 and 11 February the French areas . . . As the general situation is still in a state of flux, the further development can only be foreseen with difficulty, especially as no worth-while data from the region of Iceland are to hand.'

It is seen that the Atlantic anticyclone was still to be accounted the major steering centre as the depth and effect of the Norwegian low was not yet quite clear.

On 9 February it was clearly recognized that the Russian high had broken down and that *the high-pressure area to the west with its centre west of Ireland still remained important. The Iceland reports from the U-boats made it possible to recognize, though not unambiguously, that new disturbances would develop there.*

On 9 February the forecast up to the 14th ran in essence as follows: 'At present Holland and France lie under the influence of a mixing zone of air masses producing fog, some of it shallow. In the south of the battle area there is also a tendency to fog and lifted fog.

However, in the region of Iceland the approach of new disturbances is expected soon, whereby the development of the weather over the North Sea and over the battle area (south-east England) and above all over the Dutch base will take place more quickly'.

On 10 February it was realized that the general weather situation was controlled by the deep depression over North Scandinavia which extended to high levels. The new development west of Iceland suggested by the weather reconnaissance of 9 February, and steered south-eastwards by the large new stationary depression over Norway, had already reached Jutland. *The route for the passage of further such frontal zones was indicated.* Owing to the strong, unhindered influx of cold northerly air masses round the back of the Norwegian depression the build-up of further areas of convergence near Iceland had to be taken into account.

The forecast for 11–12 February therefore ran as follows: 'The general situation shows no change. The passage from the north and north-west of individual small disturbances embedded in the cold air stream is possible. These will make themselves felt through the dying-out of shower activity and then through temporary deteriorations in weather.

Definite timings are not possible without observations'.

Thus a weather situation was reached which for some days was expected to show certain constant elements of development and sequence. Fog and lifted fog, and slow changes in the synoptic situation which were considered unsuitable for the operation were not expected (as on 9 February), but instead more rapid changes in the region of the North Sea, with less pronounced developments in the English Channel, would certainly make sorties by the Luftwaffe possible.

With this, the alert signal was given by the meteorologists, and on the evening of 10 February Admiral of the Fleet Saalwächter, who was in charge of the operation from the naval side, together with his Chief of Staff and Admiral Ciliax, who was to take command of the ships, appeared at Field Marshal Sperrle's HQ in the Palais du Luxembourg for a conference on the start of operation 'Donnerkeil'. I personally merely presented the weather in the above terms, otherwise taking no part in the discussions, but I was present at the supper which followed. It was laid down at the meeting that on the following day, Wednesday 11 February, a decisive session, in which the Chief of Staff of the Air Fleet, Colonel Koller and I were to participate, would be held between 1200 and 1300 if all the meteorological reports had been received and processed. There was also a noteworthy discussion which gave an interesting insight into the mentality of the Navy. When Saalwächter was asked why he was determined upon the next day, he admitted with embarrassment that in any case, Friday, which also happened to be the 13th, was out of the question. No man of the Navy would give the operation a chance if it took place on such a doubly ominous day. We enlightened people of the Luftwaffe felt this very strange, especially in a war when one could certainly not be very choosy about ways and means. But because the declaration came from so authoritative a person it had to be heeded, no matter how much matters were thereby complicated.

It was thus possible on 11 February to make all the preparations necessary to ensure that all the reports would be received in good time for processing by noon on the Wednesday of the decisive briefing. The weather reconnaissance squadrons were operated so that all their reports were received by us by the latest at 1100 hours. Also for 11–12 February a reserve squadron had been detailed to fly from Brussels over the North Sea in order that the weather in the region of exit from the English Channel could be correctly appreciated. It was agreed with the Navy that all incoming reports (the U-boats were picked up from here directly) would be passed to us immediately and we would pass any to them.

It may be mentioned here that co-operation with the Naval Weather Service and their chief, Dr Süssenberger, was exemplary in every way, which, from the military viewpoint could not always be said of the Air Force and the Navy. The little jealousies which otherwise occurred between the two parts of the defence service were completely absent in the weather service. It was unfortunately a widespread phenomenon for the different offices, often including those within the Luftwaffe, to seek to play the meteorologists off one against the other. In the sphere of Air Fleet 3 this was prevented by a telephonic conference which took place daily, generally at 1600 hours, and at which the most important staff meteorologists decided on the forecasts. In our cases, naturally, a common opinion had first been agreed on between the naval meterorologist and myself, without, of course, putting anything over on our commanders. Ambitious or mutually jealous forecasters could cause great damage and they did not last long.

A sudden meteorological sensation occurred in the early morning of 11 February. The observation from the U-boat which was immediately south of Iceland reported westerly gales and low and continuously falling pressure. This was apparently a new formation, probably a so-called fast-moving wave depression. One could be fairly certain of its direction and speed because the stationary upper low over the North Cape would steer it southwards and south-eastwards, as had happened with its predecessor of the day before.

At the decisive briefing held, as arranged the day before, at 1245 (German Summer Time) I gave a verbal forecast roughly as follows (the record being made immediately after briefing), using the weather maps for clarification.

'On the basis of the 8 o'clock European Chart, in which the results of the meteorological reconnaissance squadron at Stavanger and U-boat reports south of Iceland have been incorporated, the following judgement of the weather for 12 February has been formed.

A low-pressure disturbance has formed in the region south of Iceland. Strong winds and falling pressure in the area north of Scotland suggest that in all probability this depression will move south with a speed of about 50 km/h and on 12 February between 0800 and 1000 hours will lie in the region of the eastern exit from the English Channel and will then move further south.

In the first hours of the forenoon the weather would deteriorate quickly in the Channel area and, after the passage of the front, which might take 2–4 hours, a clearance would follow quickly, while the battle area would again clear up. Conditions over the bases would deteriorate as they improved over the battle area.* In the afternoon the bases would again have favourable weather.* It is emphasized that this is the most extreme view of what may happen.'

The last sentence meant to imply that we had not wanted to set down an exact timing, but rather to sketch out clearly the extreme position in order to have a margin of safety. The naval meteorologist was concerned in his forecasts more with the western Channel region and could promise favourable weather for departure and for the night on account of the high pressure in that region.

As it had to be assumed that the ships, on keeping to plan, would have passed the 'Narrows' between 1000 and 1100 and would be able to continue sailing during the night without hindrance and that the fighter protection could be sent in, the forecast as given satisfied Admiral of the Fleet Saalwächter. He tensed, straightened himself—he was of small stature—and gave his Chief of Staff the following command:

'My decision is that you should send the code-word'.

It was exactly 1345 hours.

As will be seen from the following reports of the escape, the high over the west of the English Channel had done its bit. In consequence of the approaching low-pressure disturbance the wind had increased in the eastern Channel exit, preventing fog formation in the eastern coastal area and allowing covering fighter planes to take off as planned. Despite the fact that the deterioration took place in the east rather later than forecast, the fighters were also able to take off from the Dutch and Belgian bases in the afternoon, even if they had to contend with the same visibility difficulties as had the British attacking forces.

Perhaps it is still of interest to mention that February 1942 was exceptionally bad for all flying operations, in the main precisely because of the fog in the eastern Channel area and in Holland. The exception was a few days from 11 February onwards, when these areas were most free from fog. The good use made of the first favourable weather situation in February for the escape must be counted as a great feather in the cap of the weather service.

THE PROGRESS OF THE OPERATION

The two battleships *Scharnhorst* and *Gneisenau* and the large cruiser *Prinz Eugen* had lain since 1941 in Brest and La Palice respectively. *Prinz Eugen* had put to sea for a time with the battleship *Bismarck* on an Atlantic mission and had come, if alone, safely back to Brest. The two other ships had already come to the French Atlantic coast earlier. In consequence of the continuous air attacks by the British, carried out since 23 November 1941 (according to my record there were, up to the time of the escape of the ships, 25 more or less heavy twilight and night attacks, by which the ships were repeatedly damaged), it became impossible to allow the ships to remain at their position in Brest and a return to a home base was necessary. Since sailing from Brest to Germany lay entirely through the Channel, the idea of returning the ships to Germany this way was by no means out of consideration, although such a journey would be attended by very difficult circumstances. The voyage did, however, obviously require thorough preparation and special protection. It was the Luftwaffe which had to provide such protection.

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* Translation uncertain; the original reads as follows: Die Basis würde in gleichem Maße schlechter, als der Kampfraum wieder aufklart. Nachmittags dürfte auch die Basis wieder einwandfreies Wetter zeigen.

Thus after 1345 on Wednesday 11 February when the code-word 'Hagel' ('hail') had been given to start the action, the ships were ordered, as planned, to sail at 2000 hours (beginning of darkness).

The ships had already cast off and were setting out when the air raid warning sounded at 2040 hours. The ships hove-to again and laid down a smoke screen. About 30 British planes attacked Brest. It was naturally very important that the position of the ships should appear unchanged to the British. When the aircraft had flown away again—the ships remaining undamaged—the riddle arose 'had the British seen anything of our intention to leave, or not?'

At 2200 hours the air raid ended. We waited to see if, after the British planes had landed, any increased activity became evident at their airstrips, but everything remained quiet.

So two precious hours were lost, for the sailing could not now start before 2245 hours. The night lasted at this season of the year about 12 hours (because the ships were travelling east) so that only by the maximum speed of over 30 knots could the 360 nautical miles (approximately) to the narrowest place in the Channel be reached during night-time. But the loss of time did not prove so great, as the surprisingly favourable tides increased the speed. Thus, in the almost calm and cloudless weather resulting from the high-pressure area, and also under relatively good visibility conditions, the bold operation began at 2245 hours German Summer Time (2045 GMT).

The Commander, Admiral Ciliax was on board *Scharnhorst*. The Luftwaffe had provided him with Colonel Ibel as Fighter Commander.

After the great tension at the beginning of the operation, during the rest of the night all went quietly and according to plan. The three big ships accompanied by several destroyers and modern torpedo-boats reached the light buoy on the line Deauville–Le Havre at 0832 on 12 February 1942.

The wind freshened slowly from the south-west (almost a following wind) but the state of the sea was still slight.

At 0842 hours the first German covering aircraft took off from the airfield at Abbeville. The convoy of ships was arranged so that the great ships followed the innermost course closest to the French coast, the torpedo-boats and destroyers were deployed to the north and the E-boats, which had joined them under way, formed the extreme edge of the protection. At first the covering fighter planes flew in low in strong formations on the side which faced the enemy.

Protected in this way the convoy now approached the most dangerous place, the narrows where the Straits of Dover are only 32 km wide.

The tension in the ships and in the Operations Rooms of the Naval Group and Air Fleet in Paris grew continuously. When would the British discover the convoy?

In the meantime the British had flown their dawn reconnaissance patrol, but the routes of the reconnaissance machines were so laid out, that one machine reconnoitred the Channel Islands, which the ships had already long passed, and another Abbeville, which, at this time, the ships had not reached. Both reconnaissance planes had seen nothing, and the monitoring service reported complete quiet on the English side. On the German side during the morning extensive interference with the whole British radar service on the Channel coast had been initiated, by sending out a specially equipped plane. This would simulate the radio sound of countless German bombers; it had the fine code-name 'Garmisch–Partenkirchen' apparatus. It was sent out to the south of the Isle of Wight and was intended to draw the English fighters away from the Dover area. The British planes did take off, but only from out of the middle Channel coast and not from the London area. In fact the British had soon noticed the deception and had landed again.

The ships and aircraft naturally maintained complete radio silence. The tension grew; the narrowest place by Cap Gris Nez was passed at 1250 hours and the unbelievable happened—on the British side nothing stirred. The weather had indeed become somewhat worse and there were occasional slight rain showers and occasional lower clouds, but the English coast was visible, even if poorly so. The E-boats protecting the English coast had laid a smoke-screen, and at 1319 for the first time the British E-boats came within fighting distance. At the same time, just half an hour after the narrowest point had been passed, the first shots from the batteries at Dover fell in the neighbourhood of the ships.

In the meantime it had been realized from a radio message picked up from a British patrol boat that the convoy had been recognized as such.

By 1333 hours the convoy was already out of range of the guns of the three batteries, for the shots were falling 4 km short. From the radio reports the preparations of the Royal Air Force had been diagnosed and on the German side complete fighter protection had been commanded. Led by the best-known German fighter pilot, Galland, the fighter squadrons were deployed to a rigid plan, so that sometimes more than 30 fighters were on station above the convoy. The German planes, ME 109s (Messerschmidt) and FW 190s (Fokke-Wolf) were equipped with long-range fuel tanks and could stay in the air for 75 minutes and reach a speed of 500 km/h. Above all else it was necessary to prevent the much-feared British torpedo-carrying aircraft from reaching their goal. At 1334 *Prinz Eugen* sighted the first Swordfish torpedo-carrier. By 1350 some nine torpedo-carriers had been shot down or driven off. No damage was caused to the ships.

At 1350 hours radio silence was lifted in order to put in the full fighter support.

Just one hour later at 1455 hours, the first enemy bombers, mostly two-engined machines, were sighted. From then up to the onset of darkness the convoy was *continuously* attacked by single planes and squadrons of bombers.

Now, however, yet more shelter, of decisive importance, arrived: the weather became noticeably worse. The sky became completely overcast and rain fell. Underneath the 300 ft cloud base the visibility towards the French coast was still just good enough for the German fighters to fly. They continually attacked the British bombers as they appeared suddenly through the cloud, shooting them down or driving them off. Despite the obstinate sorties of the British planes, made doubly difficult by the bad weather, the whole force of 200–300 planes sent in caused no damage.

It is true, however, that *Scharnhorst* ran into a surface mine at 1530 hours. Luckily at this time the weather was so bad that the visibility was only 1–2 km, with cloud at 300 ft and continuous rain. Air attacks were hardly to be expected in such weather. What was worse was that the convoy must now disperse. The Admiral and his staff transfered into a destroyer and in poor visibility the ships were lost to view for long periods.

The weather had improved again locally, the visibility was now 3–4 km and at 1600 hours the British bombers began their attacks again. But the German fighters were also able to operate again and, with assistance from the ships' A.A. guns, the hostile attackers were prevented from achieving any success. Because of the more frequent bad weather areas in the north-east, with their very low cloud banks and the variable but mainly poor visibility, a united attack by bigger units on single ships was impossible. Also ineffective was the attack of the light naval forces (one light cruiser and five destroyers were reported) which took place from 1643 to 1655 hours, as the ships soon lost contact with each other.

The following incidents show how difficult it was for both sides to survey the situation in these conditions of poor visibility and with the convoy dispersed. It had been recognized from radio interceptions that British warships were approaching. A bomber squadron of the IX Fliegerkorps was sent out against the British units. At 1700 hours a German plane dropped bombs on one of its own destroyers. Also a radio message from the leader of the British naval forces was intercepted, requesting fighter protection as he was being attacked by bombers. It is, however, certain that at this time no German aircraft was over the British convoy, so that here also it could only have been one of their own aircraft which had dropped the bombs.

At 1843 hours Admiral Ciliax and his staff transferred to yet another destroyer, a difficult manœuvre in the heavy seas. And there to their joy they saw *Scharnhorst* steaming by. But at 2250 hours she again ran into a mine. At 2055 hours *Gneisenau* too had run into a mine, but despite this she was able to continue the journey at 15 knots.

The attacks of the British ended at 1910 hours and nothing more followed on the next day. At twilight there were still single German machines over the ships, and on the morning of 13 February 1942, the German fighters were able to take over the protection in quiet weather without being disturbed. In the course of the day all the ships were able to reach their allocated home bases.

Certainly things looked bad for the fighter squadrons on the evening of 12 February; of the 250 (approximately) sent in, 70 were missing according to the evening check-up. It turned out later, however, that the missing aircraft had landed at all sorts of places in Holland, as the weather had been so bad over land that only very occasionally had a return to home base been possible. The damage due to landing was, in any case, greater than that due to enemy action. The German Navy and Air Force completed a brilliant achievement, and it was not their fault that it had little effect.

BIBLIOGRAPHY

KEMP, PETER 1975 Escape of the *Scharnhorst* and *Gneisenau* (Ian Allan Ltd).

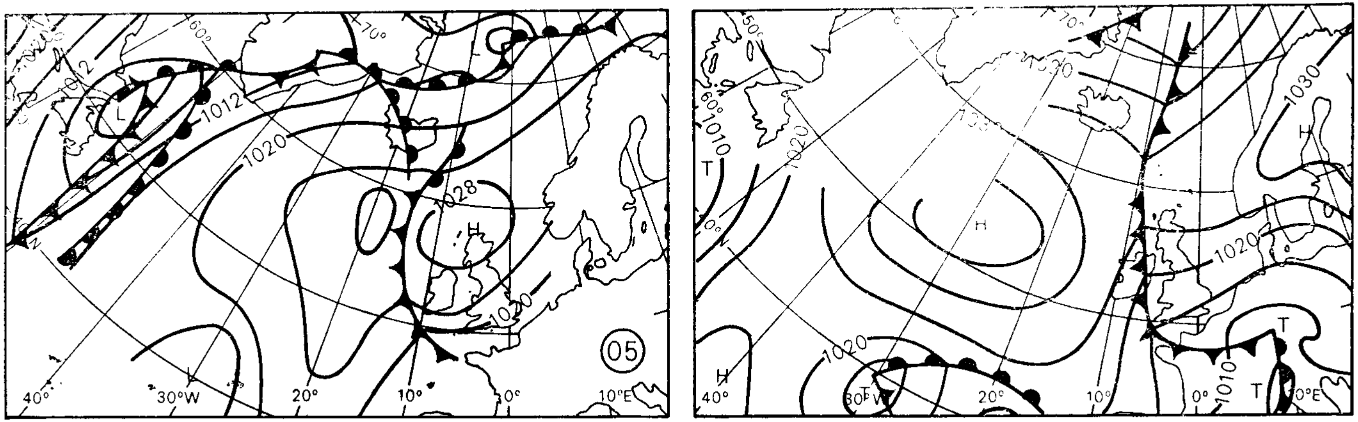

FIGURE 1—BRITISH AND GERMAN SURFACE WEATHER CHARTS FOR 5–13 FEBRUARY 1942

These charts have been copied from contemporary issues of the *Daily Weather Report* and the *Täglicher Wetterbericht*, both secret at the time but long since declassified. The British charts, with isobars at 4 mb intervals, are on the left with the day of the month in the bottom right-hand corner; the German charts, with isobars at 5 mb intervals, are on the right. The time of observation of the British charts is 00 GMT for ships and Greenland, and 01 GMT for all other areas; the time of observation for the German charts is '02 DSZ' i.e. 00 GMT. Note that on the German charts 'T' stands for 'Tiefe' i.e. a 'Low' or depression centre.

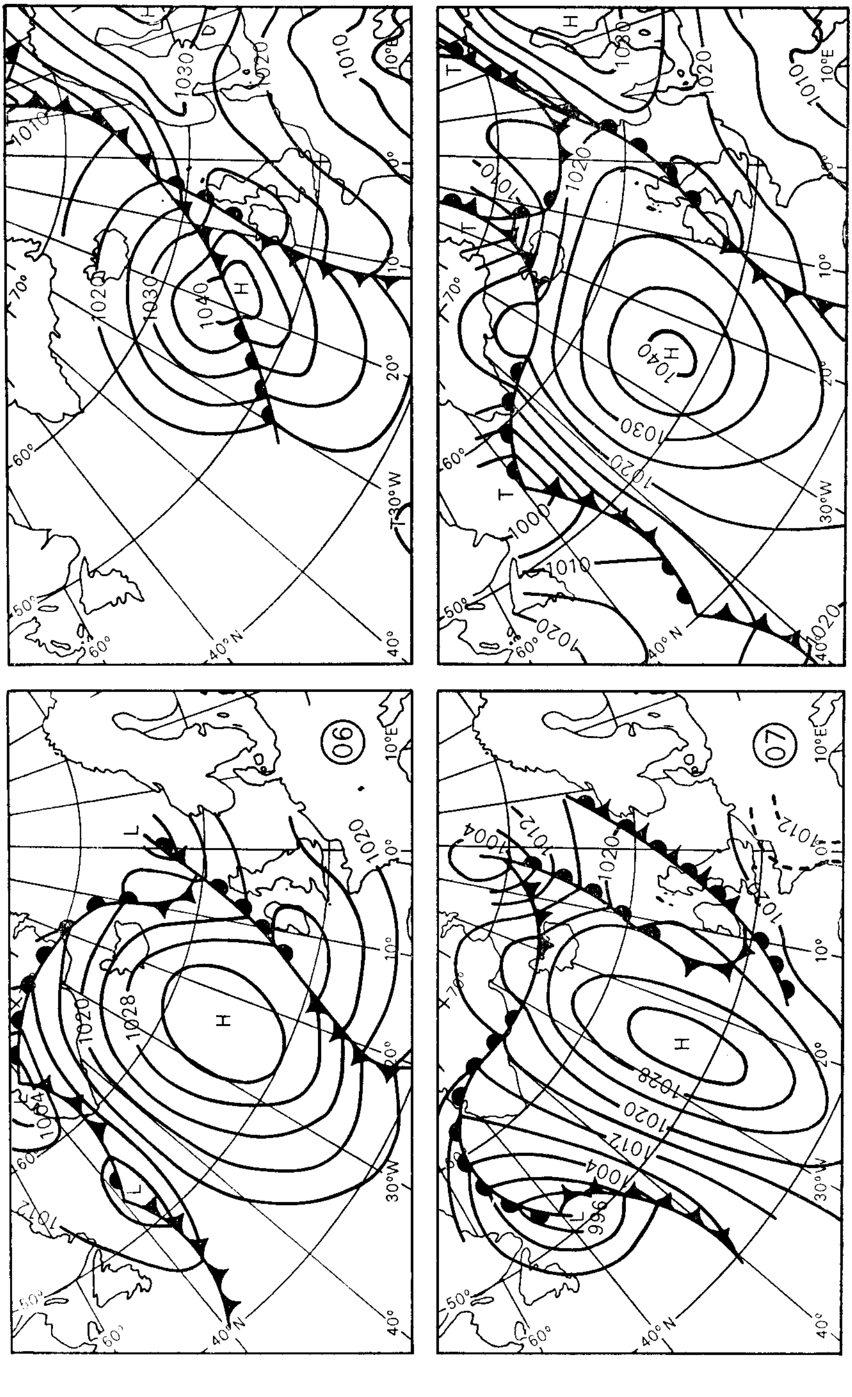

FIGURE 1—*continued*

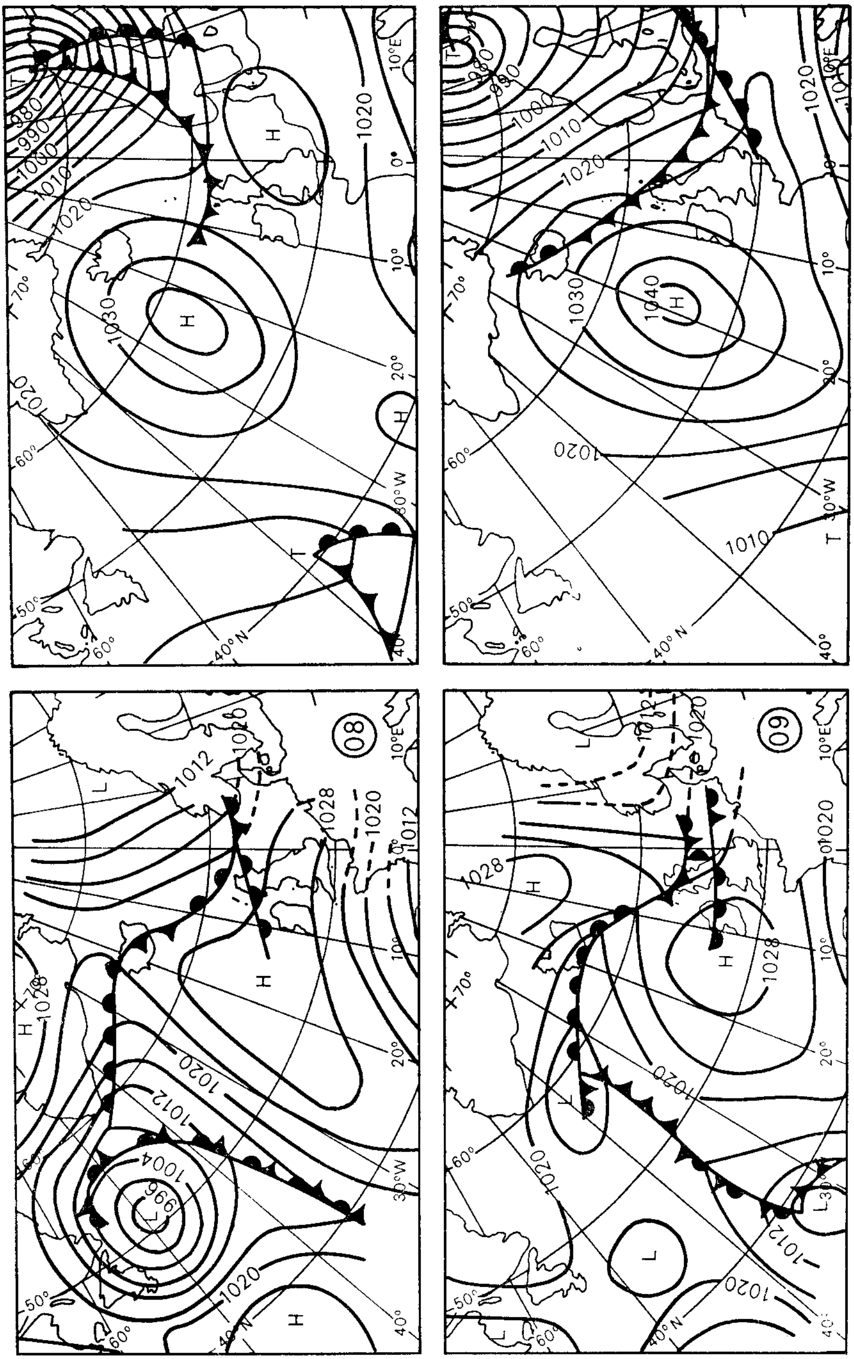

FIGURE 1—*continued*

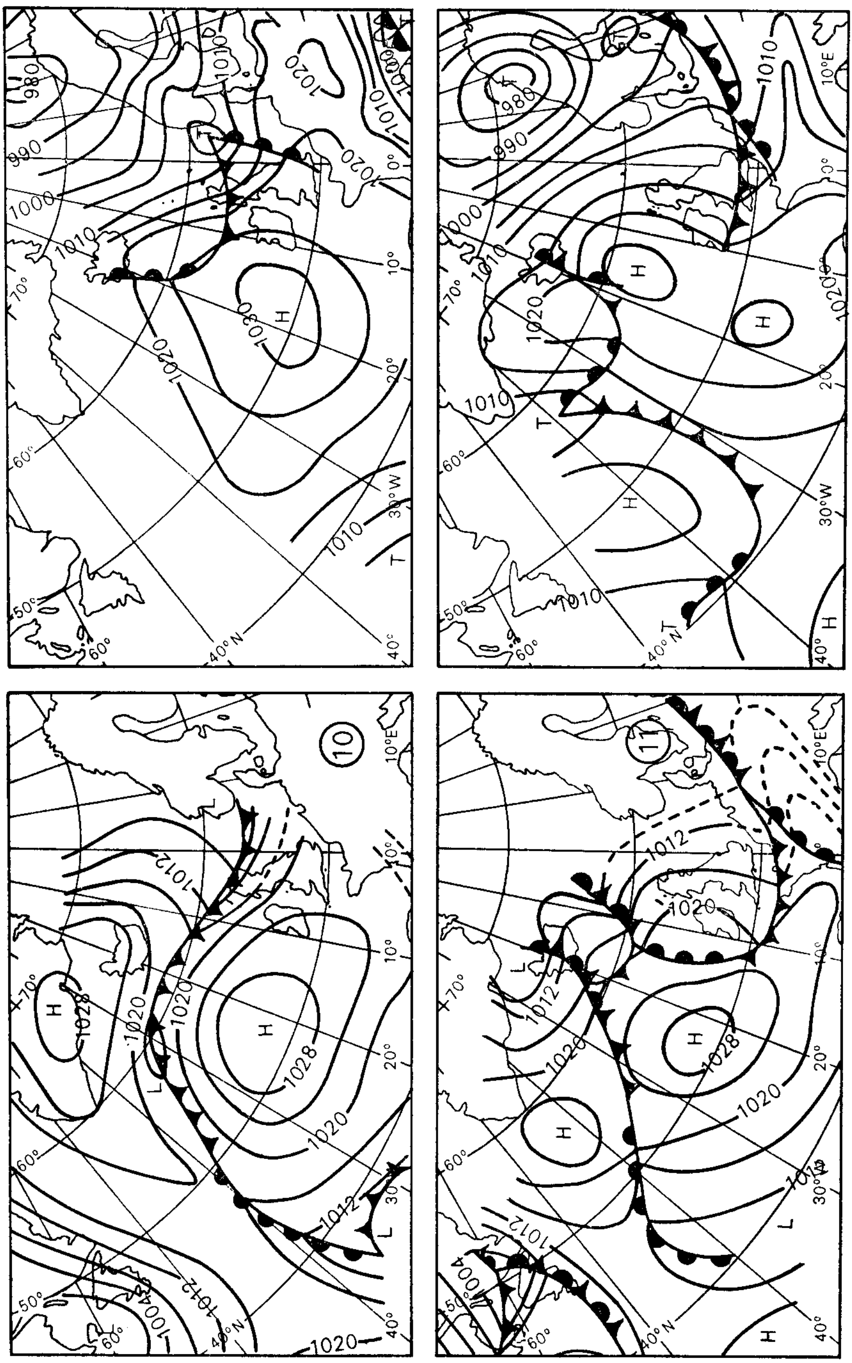

FIGURE 1—*continued*

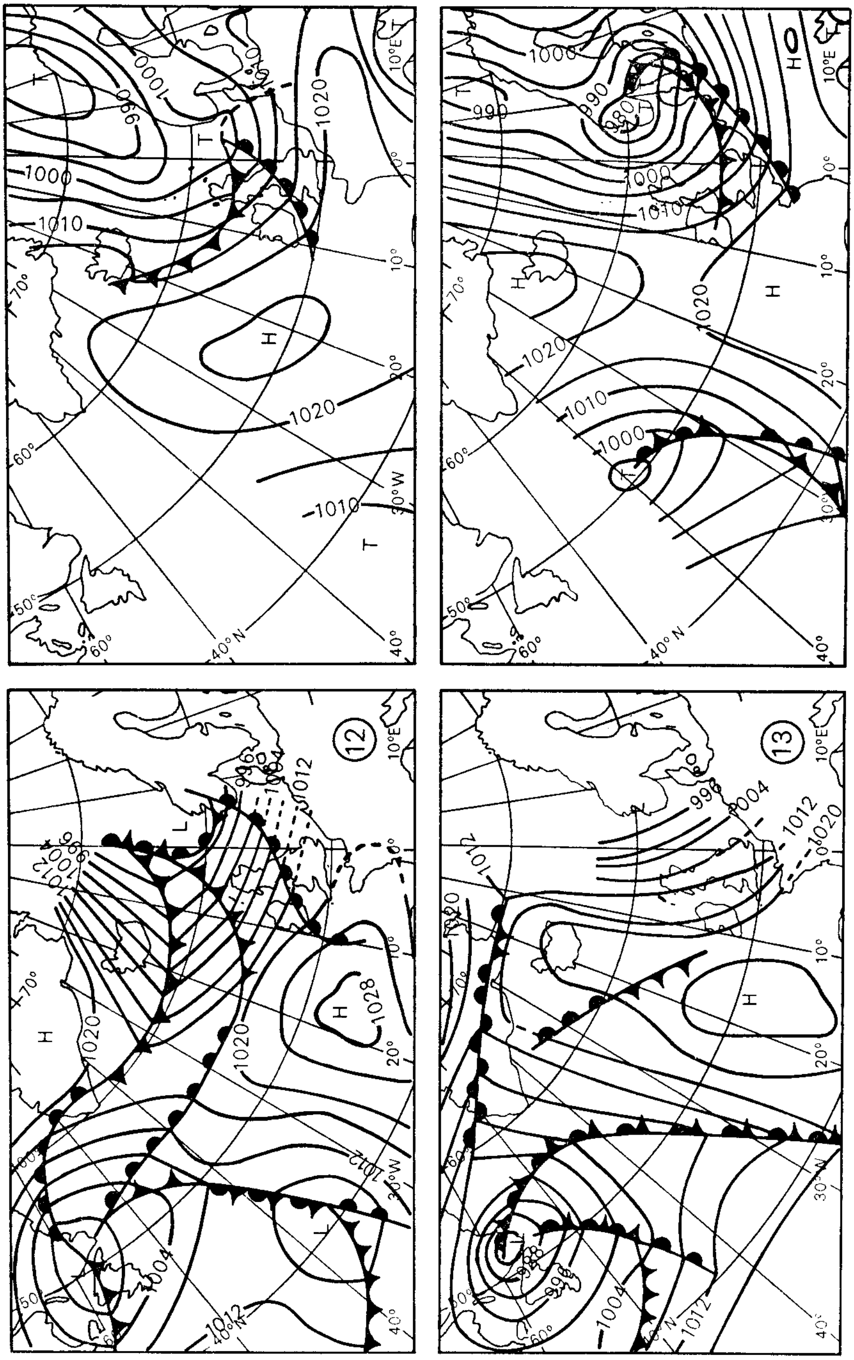

FIGURE 1—*continued*

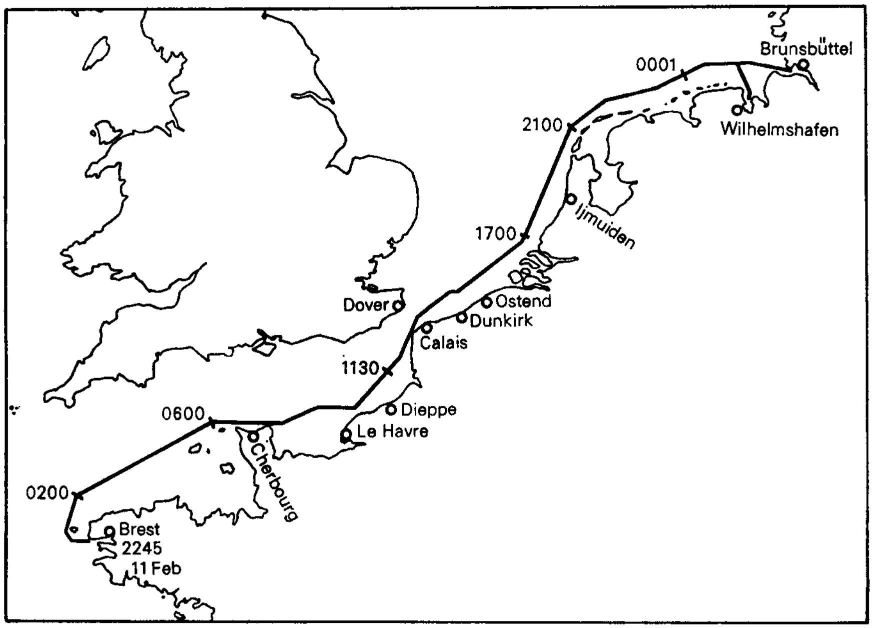

FIGURE 2—ESCAPE ROUTE OF GERMAN WARSHIPS, 11–13 FEBRUARY 1942

Times are as in text, viz. German Summer Time, two hours in advance of GMT.

551.5:06:929.6

THE METEOROLOGICAL OFFICE BADGE

By R. P. W. LEWIS

A new design for the official badge of the Meteorological Office was brought into use early in 1978 and we thought it would be of interest to our readers if we gave a short account of how this and earlier designs arose.

In 1910 the Office moved into its new premises in Exhibition Road, South Kensington. The Director at the time was Dr W. N. (later Sir Napier) Shaw. We have received a letter from Mr H. L. B. Tarrant, who served from 1902 to 1948 and became Chief Clerk, and in it he says that after the move '... we had on the staff a Miss Humphries* (a draughtswoman)* and I think that when Dr Shaw (as he was then) decided that the Office should have a crest†, Miss Humphries produced some designs under his directions. However, I think the final design, and the plaques, were produced by the Bromsgrove Guild to whom Dr Shaw referred the matter for professional advice'.

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* Listed in the *Annual Report* as 'Miss E. C. Humphreys, Photographic Assistant'.
† Mr Tarrant uses the term 'crest' incorrectly for 'badge'. A crest, though it may be displayed separately, exists not in its own right but only as part of a complete achievement of arms containing at the very least a shield or 'coat of arms'. See e.g. MacKinnon (1966).

PLATE I—ORIGINAL METEOROLOGICAL OFFICE EMBLEM

This wooden plaque is one of two made in 1911 for the new office in South Kensington and is now housed in the Cartographic Drawing Office at Meteorological Office Headquarters. (See page 339.)

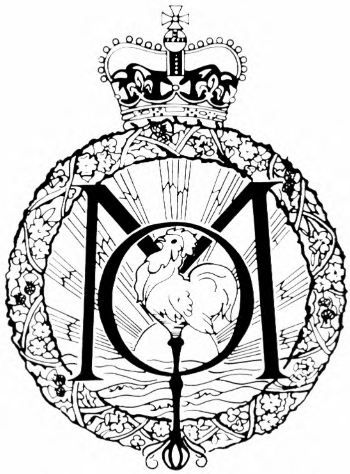

Plate II—Old Meteorological Office Badge

A recent version of a design based on the wooden plaque of 1911. (See page 339.)

Plate III—New Meteorological Office Badge

This design was introduced in 1978. It was produced by the Graphic Design Division of Her Majesty's Stationery Office. (See page 339.)

PLATE IV—HANDOVER OF THE MK 3 RADIOSONDE SYSTEM

Mr P. Dorey, Managing Director, Ferranti Computer Systems Ltd, signs the formal handover document for Mk 3 radiosonde watched by, on his right, Mr F. H. Bushby, Director of Services of the Meteorological Office, on his left, Mr B. O. Penny, AD/SLR 3, and standing, Dr D. N. Axford, AD Met O (OI). (See page 355.)

PLATE V—HANDOVER OF THE MK 3 RADIOSONDE SYSTEM

Dr R. E. W. Pettifer (Mk 3 radiosonde Project Manager) launches the demonstration sonde watched by Mr P. Dorey, Managing Director, Ferranti Computer Systems Ltd, and Mr I. Ball, General Manager, Ferranti Computer Systems Ltd. (See page 355.)

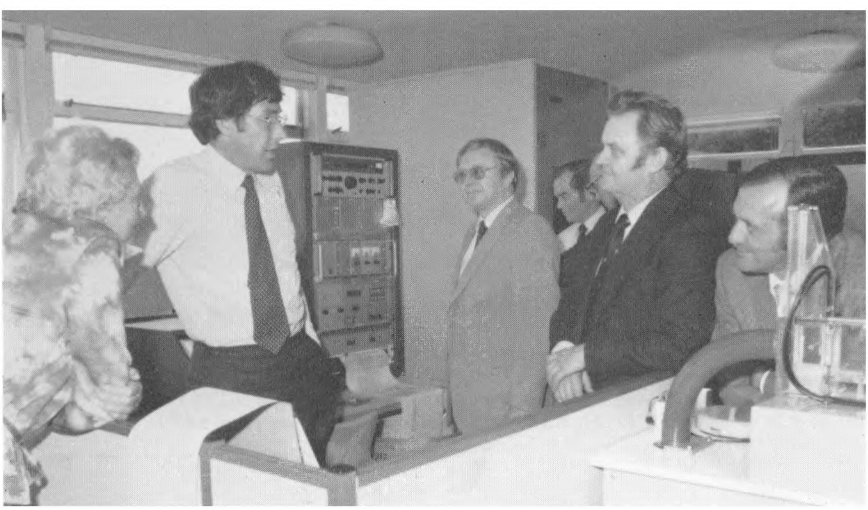

PLATE VI—HANDOVER OF THE MK 3 RADIOSONDE SYSTEM

Dr R. E. W. Pettifer (Mk 3 radiosonde Project Manager) describes the progress of the demonstration flight to, from left to right, Miss L. M. Abrey (S9 (Air)), Mr P. Dorey, Managing Director, Ferranti Computer Systems Ltd, Mr I. Ball, General Manager, Ferranti Computer Systems Ltd, and Mr B. O. Penny, AD/SLR 3. (See page 355.)

The *Annual Report of the Meteorological Committee* for 1911–12 and the Minutes of the Committee confirm that the work was executed by the Bromsgrove Guild and add that it was paid for by private subscription and administered on behalf of the Meteorological Office by the architects' department of the Office of Works. The plaques to which Mr Tarrant refers were two in number and made of wood; they were displayed in the Library, one over each door. One plaque is still in existence and is housed in the Cartographic Section (Met O 18d); it is shown in Plate I.

(The Bromsgrove Guild, who used to do a great deal of work of this kind, arose from William Morris's group of craftsmen in Victorian days; some years ago it was absorbed into the Bromsgrove Casting and Machinery Company and no relevant records survive.)

During the next few years the plaque design was used as the basis for various small logotypes which were printed on publications. A version was used, for example, on the *Meteorological Office Circular* issued from 1917 to 1919, and then on the title page of the *Meteorological Magazine* when this became the official journal of the Office in 1920 following the take-over of Symons's 'British Rainfall Organization'; it was used on the *Daily Weather Report* from April 1919.

A larger and more elaborate version was first used on the cover of the *Meteorological Magazine* in February 1939. Other versions with minor variations occur here and there: stamped on official bindings, as a blazer badge, and so on. A recent version is shown in Plate II.

A few years ago demand began to grow for the Meteorological Office to display its own official badge on RAF premises and on the aircraft of the Meteorological Research Flight. The apparently obvious answer, namely to use a version of the old design for the plaque, turned out to be impossible because the design had never received the official recognition of the College of Arms and it is not permissible for unofficial designs to be used on aircraft or other RAF property.

The advice was sought of the Graphic Design Division at Her Majesty's Stationery Office (HMSO) who recommended that a new design should be produced, based on important elements in the old one, but clean, simple, and modern in appearance, and able to function as a logotype for official stationery as well as on a flag or on an aircraft. After one or two false starts a suitable design was produced by Mr Peter Branfield of HMSO in consultation with Met O 18, and this is illustrated in Plate III.

In December 1977 we were informed that the Property Services Agency and Garter King of Arms had approved the design for all official purposes and in consequence of this decision the RAF later agreed that it might be displayed on MRF aircraft.

Reference

MACKINNON, C. 1966 The Observer's Book of Heraldry. London, Frederick Warne and Co. Ltd.

551.558.21:629.734

WEATHER CONDITIONS FOR LONG GLIDING FLIGHTS OVER ENGLAND

By T. A. M. BRADBURY
(Meteorological Office, Bracknell)

SUMMARY

An analysis was made of weather conditions suitable for closed-circuit gliding flights of more than 200 km over England. The best conditions were found when vigorous convection developed in a relatively shallow layer extending from the surface to about 2 km provided that the wind speed in this layer did not exceed 10 m s^{-1}, the cloud base was more than 1 km above the general ground level, and more than 50 per cent of the possible sunshine was recorded. The synoptic situations most likely to provide these conditions occurred after the passage of a cold front where a ridge or small anticyclone developed.

INTRODUCTION

In recent years there has been a steady increase in the number of cross-country flights attempted by glider pilots. Before 1960 nearly all long flights were made downwind but recently the majority of flights have been planned as closed circuits round one or more previously declared turning points. In 1976 there were 493 cross-country flights from one gliding site alone. The average distance covered was 230 km but a number of flights exceeded 500 km and one covered 801 km.

On a fine summer weekend there may be over one hundred gliders making cross-country flights over England. Many pilots rely on forecasts issued to their club by a meteorological office or simply listen to bulletins issued by the BBC but some pilots regularly consult a forecast office before planning a long flight. Forecasters may find it useful to know the conditions found most favourable for long closed-circuit flights and the synoptic situations most likely to provide these conditions.

DATA

The dates of all cross-country flights of more than 200 km were taken from the Lasham Gliding Society log for the years 1975 to 1977. Flights which exceeded 399 km were listed separately; since these were much less frequent the period was extended back to 1968 in order to collect a large enough sample. In the tables which follow these are referred to as '$\geqslant$400 km days'. It is justifiable to assume that conditions were particularly good when the longer flights were made but the converse is not necessarily true. Equally good conditions may have occurred on other days which might have been included in the '$\geqslant$400 km list had there been sufficiently experienced pilots free to fly them. Meteorological data were taken from the *Daily Weather Report* and the *Daily Aerological Record*, supplemented by specially plotted charts and tephigrams on a few outstanding days. Low-level soundings made by balloon at Cardington were found useful for studying the changes in stability of the air between early morning and late afternoon but these soundings never reached the top of the convective layer on good soaring days.

CONDITIONS NEEDED FOR LONG CROSS-COUNTRY FLIGHTS

All the flights made use of the convective upcurrents known as 'thermals'. In the USA and New Zealand very long gliding flights have been made in lee waves or along the slopes of extensive mountain ranges but the vast majority of cross-country flights over England relied on 'thermals' exclusively. On some days a few pilots were able to climb from thermals into waves which extended far above the convective layer but these flights represented only a tiny fraction of the total. These exceptions are not thought to invalidate the list of essential conditions which follows.

(a) Convective currents rising from the surface must be strong enough to lift a glider at 2 m s^{-1} (4 knots) or more. These currents must be distributed fairly regularly over a wide area and convective activity must continue for most of the day.

(b) Wind speeds in the convective layer must be low compared to the cruising speed of the glider. If the wind speed exceeds 10 m s^{-1} (about 20 knots) most pilots find it difficult to complete long closed-circuit flights.

(c) The cloud base must be high enough for glider pilots to continue their undulating progress of climbs and descents without the need to enter cloud or risk a premature landing. Almost all long cross-country flights oblige pilots to pass under or through airways radiating out from London and other major cities. Since gliders cannot be flown in accordance with Instrument Flight Regulations the pilots must remain well clear of cloud when crossing airways. In many cases this requires a pilot to stay 1000 ft below cloud.

Unless the cloud base rises to at least 1 km (approximately 3300 ft) by early afternoon it is difficult to complete a long cross-country flight and most good soaring days were distinguished by cloud bases of 1·5 km (5000 ft) or more.

FACTORS FAVOURABLE FOR CROSS-COUNTRY GLIDING

Previous trajectory of air mass

On most days the air over England had come from a colder region. The approximate direction from which the air had come was estimated from six-hourly charts and tabulated under eight directions. If the air appeared to have spent more than 24 hours over the country it was classified under 'local'. The results are shown in the following table.

TABLE I—FREQUENCY OF AIR TRAJECTORIES FROM DIFFERENT POINTS

	N	NE	E	SE	S	SW	W	NW	Local	Total
					Number of days					
Flights of										
200–399 km	16	3	15	2	0	1	16	18	17	88
⩾ 400 km	29	14	5	0	0	1	15	16	7	87
All	45	17	20	2	0	2	31	34	24	175

The table shows that relatively warm winds from a southerly point very rarely provided good soaring conditions. Air from the north-east gave several outstandingly good days in spring or early summer when the freezing level was very low but subsidence and relatively dry air prevented shower development.

Wind speeds

If the wind in the convective layer exceeded 10 m s^{-1} (approximately 20 knots) the chance of a glider successfully completing a long closed-circuit flight appeared to be much reduced. Since wind speeds are given in knots for aviation purposes these units have been used in the following table.

TABLE II—FREQUENCY OF 850 mb WIND SPEED ON GOOD SOARING DAYS (AT MIDDAY)

	Speed range (knots)								
	1–5	6–10	11–15	16–20	21–25	26–30	31–35	36–40	Total
	Number of days								
Flights of									
200–399 km	17	25	22	14	8	1	0	1*	88
⩾ 400 km	11	33	25	12	5	1	0	0	87
All	28	58	47	26	13	2	0	1	175

The figure marked with an asterisk in the right-hand speed column of Table II represents an occasion when a pilot was able to make exceptionally good progress into wind by following a long line of active cumulus clouds (base 6000 ft). The line of rising air associated with such cumulus 'streets' often makes it unnecessary to circle to gain height.

It will be seen that more than 90 per cent of all flights took place when the 850 mb wind was not more than 20 knots. Closer examination of the strong-wind days showed that either winds were decreasing markedly between 12 and 18 GMT or there was a significant decrease in the wind just below the 850 mb level.

TABLE III—FREQUENCY OF 850 mb WIND DIRECTIONS AT MIDDAY (FOR SPEEDS OF 10 KNOTS OR MORE)

	Wind directions									
	N	NE	E	SE	S	SW	W	NW	under 10 knots	Total
	Number of days									
Flights of										
200–399 km	10	12	4	2	2	8	6	9	35	88
⩾ 400 km	12	13	7	1	2	0	8	9	35	87
All	22	25	11	3	4	8	14	18	70	175

It may be seen that the longer flights were very rare if the 850 mb wind was between south-east and south-west.

Curvature of isobars

The best soaring conditions were usually associated with ridges or small anticyclones. The curvature of isobars appeared to be one of the best single indicators of good soaring weather. It was found impracticable to set a strict numerical value to the curvature over a small area such as England because the majority of charts used were on a scale of 1 : 20 or 1 : 30 million with isobars at 4 mb intervals. In the following table the amount of curvature has been classed as either marked or slight. The six columns range from marked anticyclonic through straight isobars to marked cyclonic curvature. Areas with a very flat distribution of pressure were listed under 'no gradient'. These were often cols.

TABLE IV—FREQUENCY OF ISOBARIC CURVATURES ON GOOD SOARING DAYS

	Anticyclonic		Straight	No gradient	Cyclonic	
	marked	slight			slight	marked
	Number of days					
Flights of						
200–399 km	17	30	18	18	5	0
⩾ 400 km	56	20	3	4	4	0
All	73	50	21	22	9	0

This shows that there was anticyclonic curvature on most of the cross-country days and the curvature was marked on most days when flights reached or exceeded 400 km. A survey of every day from March to mid-September 1976 showed that the days of most sunshine were associated with anticyclonic curvature. In most other less sunny years it was common to find that even a small and transient ridge prevented showers from developing in an apparently very unstable air mass.

Surface pressure

Above average values of surface pressure were often associated with anticyclonic curvature of the isobars. On good soaring days the mean sea-level pressure had an average value about ten millibars above the normal. On a few days a lower than normal surface pressure combined with an isobaric ridge allowed good soaring conditions to develop.

TABLE V—FREQUENCY OF MEAN-SEA-LEVEL PRESSURES ON GOOD SOARING DAYS

	Pressure range (millibars)						
	1001–05	1006–10	1011–15	1016–20	1021–25	1026–30	1031–35
	Number of days						
Flights of							
200–399 km	0	12	20	29	18	6	3
⩾ 400 km	1	3	9	19	36	14	5
All	1	15	29	48	54	20	8

Nearly 80 per cent of the ⩾ 400 km flights took place when pressure was in the range 1016–1030 mb. The peak in the range 1021–25 mb is more pronounced for the longer flights. All flights showed a sharp cut-off just above 1033 mb; this was probably due to anticyclonic subsidence bringing the inversion down well below 850 mb.

Pressure tendency

Pressure changes were small on the majority of good soaring days. If the passage of a cold front was followed by a large rise of pressure the arrival of good soaring conditions was often delayed until the approach of an anticyclone or its associated ridge. Several outstandingly good days occurred about 24 hours before the arrival of a warm front when the pressure was just about to fall.

TABLE VI—FREQUENCY OF PRESSURE CHANGES 09–12 GMT ON GOOD SOARING DAYS

	3-hour tendency (millibars)										
	+2·2 to +1·8	+1·7 to +1·3	+1·2 to +0·8	+0·7 to +0·3	+0·2 to −0·2	−0·3 to −0·7	−0·8 to −1·2	−1·3 to −1·7	−1·8 to −2·2	−2·3 to −2·7	−2·8 to −3·2	Total
	Number of days											
Flights of												
200–399 km	1	3	9	6	17	31	15	3	0	3	0	88
⩾ 400 km	0	1	3	11	22	32	11	6	0	0	1	87
All	1	4	12	17	39	63	26	9	0	3	1	175

Nearly 90 per cent of all flights occurred on days when the midday pressure tendency lay within the range +1·2 to −1·2 mb.

Stability of the air mass

On most afternoons the air was unstable from the surface to above the 850 mb level but the depth of convection was restricted by a stable layer below the 700 mb level. The decrease of potential temperature between the surface and 850 mb has been found a useful indicator of the strength of thermals (Higgins 1963, Booth 1978). The average decrease of θ between the surface and 850 mb was 2·8 °C (standard deviation 1·88 °C) on $\geqslant$ 400 km days and 2·2 °C (standard deviation 1·60 °C) on 200–399 km days. These values are close to the figure of 2·54 °C quoted by Booth for the surface to 1500 m layer on days of good thermals. During the summer the height of the 850 mb surface is usually close to 1500 m. The superadiabatic lapse rate did not usually extend far above the surface and for most of its depth the convective layer had a near adiabatic lapse rate.

Humidity

On most good soaring days the air was relatively dry. Low humidity is normally associated with small amounts of cloud and a high cloud base during the afternoon. The most useful measure of humidity for gliding forecasts was found to be the difference between the dry-bulb temperature and the dew-point at the surface. When the surface temperature is rising this difference can be used to obtain the approximate condensation level (and hence the base of convective cloud) from a simple formula:

$$H = 400(T - T_d)$$

where H is the height in feet, T is the dry-bulb temperature in degrees Celsius and T_d is the dew-point in degrees Celsius. Although the values obtained from this formula are not exact they have been found to be fairly close to those reported by glider pilots for the general level of cumulus bases.

TABLE VII—FREQUENCY OF DIFFERENCES BETWEEN SURFACE DRY BULB AND DEW-POINT AT TIME OF MAXIMUM TEMPERATURE

	Temperature difference (°C)								
	7–8	9–10	11–12	13–14	15–16	17–18	19–20	21–22	Total
	Number of days								
Flights of									
200–399 km	5	8	21	25	9	12	4	4	88
$\geqslant$ 400 km	1	7	29	19	21	6	3	1	87
All	6	15	50	44	30	18	7	5	175

From this one may infer that the general level of the cloud base rose to above 4000 ft (above 1200 m) by mid-afternoon on all but 12 per cent of days. Some forecasters may be surprised by the very high condensation levels implied by this table. On a number of days the air was too dry for any convective cloud to form, but there were numerous reports of cloud bases at or above 6000 ft (approximately 1800 m). During the remarkable drought in summer 1976 several glider pilots observed that the base of cumulus cloud was above 10 000 ft (approximately 3 km) on very hot days.

Lack of surface moisture

A large proportion of the net radiation received at ground level is absorbed as latent heat used for evapotranspiration when the surface is moist and covered with growing vegetation. Less energy is converted into latent heat when the ground is dry; this leaves more sensible heat available for producing thermals. The effect of the long drought in summer 1976 was most marked. Large areas of country turned brown, showing that there was insufficient soil moisture for many plants to continue growing. Pilots found that thermals extended higher than usual and cross-country flights were possible on almost twice as many days as usual.

In contrast when the surface is covered by well-irrigated crops almost all the net radiation received during the afternoon may be converted into latent heat used for evapotranspiration (Brooks and Goddard, 1966). American glider pilots have reported that thermals are never found over or just to the lee of such irrigated areas in the middle west of the USA (Moffat, 1974).

When flights of 200–399 km were made the state of ground was reported as dry on 72 per cent of the days and there was no measurable rain on 92 per cent of the days. For flights equalling or exceeding 400 km the figures for dry ground were 76 per cent and for no measurable rain 97 per cent. These figures are similar to those reported for central France (Malpas, 1977).

Sunshine

It appears that a regular supply of thermals is unlikely unless there is bright sunshine for more than half the daylight hours. Some long flights have been carried out under an almost overcast sky but the distribution of thermals is seldom adequate and pilots usually have to fly slowly and waste time searching for upcurrents.

TABLE VIII—FREQUENCY OF HOURS OF SUNSHINE RECORDED ON GOOD SOARING DAYS

	Sunshine duration (hours)								
	0–1·9	2–3·9	4–5·9	6–7·9	8–9·9	10–11·9	12–13·9	14–15·9	Total
	Number of days								
Flights of									
200–399 km	1	3	3	19	20	20	13	9	88
⩾ 400 km	0	0	3	6	11	21	37	9	87
All	1	3	6	25	31	41	50	18	175

Seventy-seven per cent of the occasions when flights equalled or exceeded 400 km had 10 or more hours of sunshine.

Visibility

Good visibility is important to glider pilots both for keeping on track and for recognizing the areas of good and poor convective activity from the appearance of cumulus clouds ahead. Poor visibility not only hinders navigation and cloud recognition but often marks regions of reduced thermal strength. It is common to find that a decrease in visibility also coincides with weakening thermals and many pilots have remarked on the decrease in thermal strength in the areas of industrial haze downwind of large cities such as Birmingham.

It is probable that haze not only reduces insolation at ground level but also absorbs heat near the top of the haze layer. This reduces the lapse rate between the surface and the haze top and weakens convective mixing (Venkatram and Viskanta 1977, Glazier *et alii* 1976).

TABLE IX—FREQUENCY OF VISIBILITIES AT 12 GMT ON GOOD SOARING DAYS

	Visibility range (kilometres)								
	< 10	10–14	15–19	20–29	30–39	40–49	50–59	⩾60	Total
	Number of days								
Flights of									
200–399 km	2	9	11	23	14	12	15	2	88
⩾ 400 km	0	2	13	15	15	25	11	6	87
All	2	11	24	38	29	37	26	8	175

This table shows that only a small percentage of flights took place when the visibility was less than 15 km. The majority of long flights occurred on days when the visibility was better than 30 km.

SIMILARITIES BETWEEN SYNOPTIC SITUATIONS IN ENGLAND AND CONTINENTAL AREAS ON GOOD SOARING DAYS

Many of the synoptic features which were observed to produce good soaring conditions over England appeared to be equally effective over continental regions. Lindsay (1969) described weather types favourable for cross-country soaring over the eastern part of the USA but did not consider wind speed since practically all the flights were made downwind. Kreipl (1976) gave a number of synoptic charts showing the situation over Germany on record-breaking days. Malpas (1977) produced a statistical summary of days when pilots completed closed-circuit flights of 300 km or more over central France. He noted that the 850 mb wind was less than 21 knots on 90 per cent of days, southerly winds were the least favourable and the most commonly observed mean-sea-level pressures were in the range 1022 to 1025 mb.

DIAGRAMS FOR THE PREDICTION OF CROSS-COUNTRY CONDITIONS

The data from which the preceding tables were compiled have been combined to produce three prediction diagrams. These diagrams are divided into sectors marked GOOD, FAIR, POOR, BAD and NIL to indicate the prospects of a successful flight. The shape of the sectors depends on the position of the original plots; the size of the sectors depends on the number of days counted within the various boundaries. Sixty-five per cent of all days fell in the 'GOOD' sector, 15 per cent in the 'FAIR' sector and a further 15 per cent in the 'POOR' sector making a total of 95 per cent. The remaining 5 per cent were scattered in the sector marked 'BAD'.

Figure 1 is intended to show the cross-country prospects based on a combination of the past trajectory of the air and the future isobaric curvature. It requires a series of analysed charts together with the latest forecast chart. The previous trajectory of the air approaching the country is shown along the y-axis under eight main compass points. The expected isobaric curvature (obtained from a forecast chart) is marked on the x-axis. This curvature is divided into six classes indicated by symbols and letters. The classes range from markedly anticyclonic (A) through straight isobars (str) to markedly cyclonic (C). During the summer cols were sometimes associated with thunderstorms and for this reason a col was ranked between straight isobars and cyclonically curved isobars. Large thunderstorms may ruin the prospects for cross-country flights because a number of cumulonimbus cells can form a barrier which is both dangerous to cross and difficult to avoid.

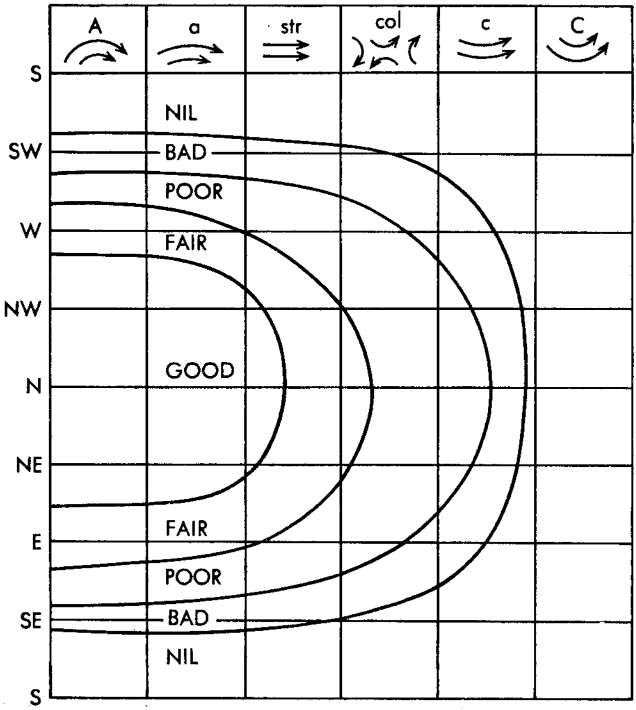

FIGURE 1—PROSPECTS FOR LONG CROSS-COUNTRY FLIGHTS BASED ON PREVIOUS AIR TRAJECTORY AND EXPECTED ISOBARIC CURVATURE

Figure 2 shows the effect of the 850 mb wind on the prospects for closed-circuit flights. The wind speed is shown along the *x*-axis and the wind direction along the *y*-axis. The adverse effect of a headwind varies in proportion to the cruising speed of the glider. The optimum cruising speed of a glider is calculated from its performance curves and the rate of climb, modified by any vertical motion of the air through which the glider is flying (Welch, Welch and Irving, 1977). The best speed at which to fly is usually displayed instrumentally and may vary between about 55 and 100 knots depending on the rate of climb. The greater the rate of climb the faster will be the optimum speed.

Strong thermals enable a pilot to climb rapidly and cruise fast between thermals. If thermals are weak the rate of climb will be slow and the optimum cruising speed correspondingly reduced. The pilot thus suffers a double handicap in weak thermals because the longer he spends circling in a thermal the further downwind he drifts and the slower is his optimum speed after leaving the thermal.

Figure 2 shows that when the wind direction lay in the sector from 290° through 360° to 070° the strength of thermals was often adequate for flights into wind. In contrast when the wind direction was southerly thermals were seldom adequate and the prospects of completing a closed-circuit flight were reduced.

Figure 3 shows the effects of the variation in stability and low-level moisture. The change in potential temperature between the surface and the 850 mb level at the time of maximum temperature is shown along the *x*-axis. Positive values

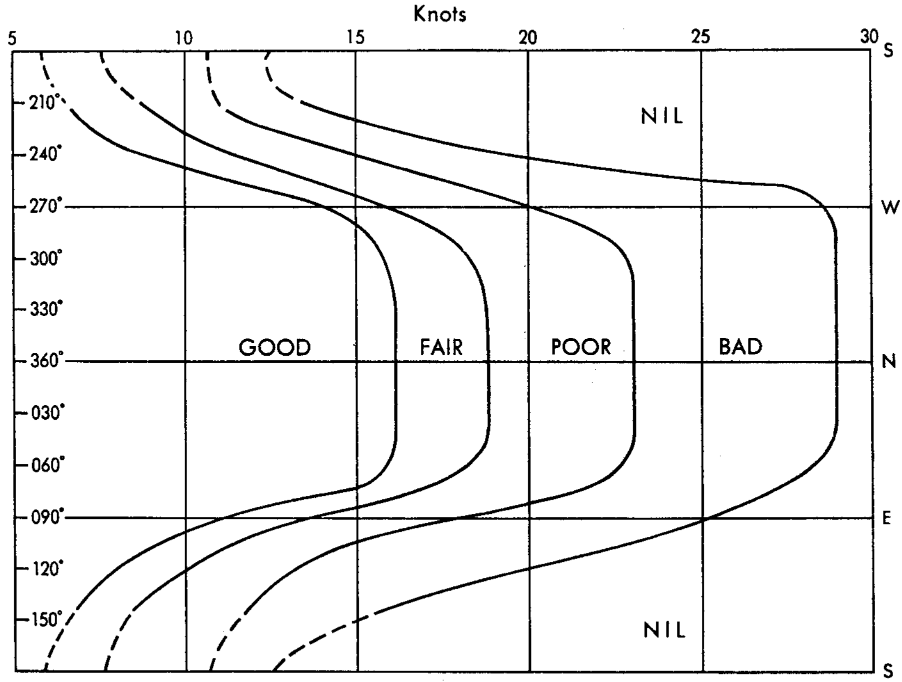

FIGURE 2—PROSPECTS FOR LONG CLOSED-CIRCUIT FLIGHTS BASED ON 850 mb WIND SPEED AND DIRECTION

indicate a superadiabatic lapse rate. The dew-point depression at the surface is shown along the y-axis. These two parameters were combined because it is important that the air should be both unstable and relatively dry for good soaring conditions. If the air is moist and unstable the condensation level will be low and the cloud amount is likely to become excessive.

There were a few days when the value $\theta_{surface}-\theta_{850}$ was negative, showing that a stable layer existed below the 850 mb level. On such days pilots often noticed that the base of the stable layer rose during the afternoon so that the midday sounding was not truly representative of conditions later in the afternoon. This effect has long been known (Ball 1960, Rayment and Readings 1974); it may have caused the degree of low-level instability to be underestimated on some occasions.

A METHOD OF COMBINING THE PREDICTION DIAGRAMS

The three prediction diagrams may be used in combination to derive a total mark for the day. The system proposed is rudimentary but it is hard to justify attempts at precise figures when assessing the chances of a project as uncertain as a gliding flight. Marks are allotted as 3 for a 'GOOD', 2 for a 'FAIR', 1 for a 'POOR' and 0 for a 'BAD'. If at any stage NIL is encountered the total mark is reduced to zero. After summing the marks for each diagram an extra mark is

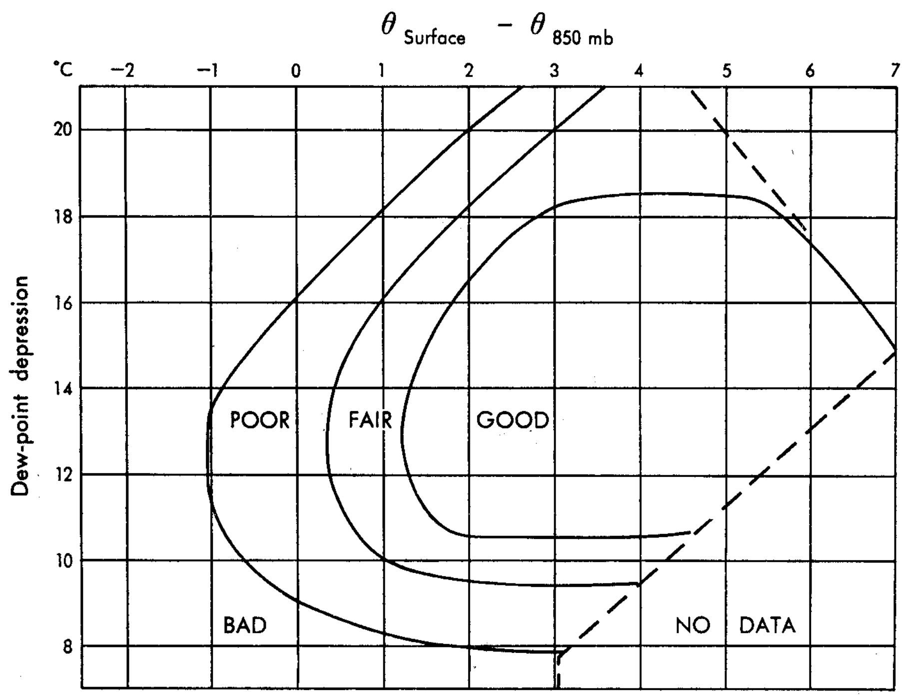

FIGURE 3—PROSPECTS FOR LONG CROSS-COUNTRY FLIGHTS BASED ON THE POTENTIAL TEMPERATURE DIFFERENCE BETWEEN THE SURFACE AND 850 mb AND THE DEW-POINT DEPRESSION AT THE SURFACE AT THE TIME OF MAXIMUM TEMPERATURE

allotted if the pressure lies in the favourable range 1016 to 1030 mb. This brings the total to 10 if every indication is favourable. When applied to ⩾ 400 km days the marks fell as follows:

Marks	0	1	2	3	4	5	6	7	8	9	10
No. of days	0	0	0	0	2	4	9	10	15	21	26

It may be seen that more than 80 per cent of occasions scored 7 marks or more.

USE OF UPPER-AIR CHARTS

The 850 mb isotherms were found useful for estimating the advective changes to be expected in the convective layer. A cold tongue in the pattern of isotherms usually marked a region of vigorous convective activity. When this cold tongue lay beneath an advancing upper ridge the convection was usually confined to a relatively shallow layer because middle-level subsidence provided a 'lid'. Figure 4 shows an example of this type of situation. The 300 mb contours have been superimposed on the pattern of 850 mb isotherms. Particularly good soaring conditions were observed near the axis of the cold tongue at 850 mb.

It might be thought that lower than normal temperatures at the 850 mb level would be a useful indication of good soaring weather. This was nearly always

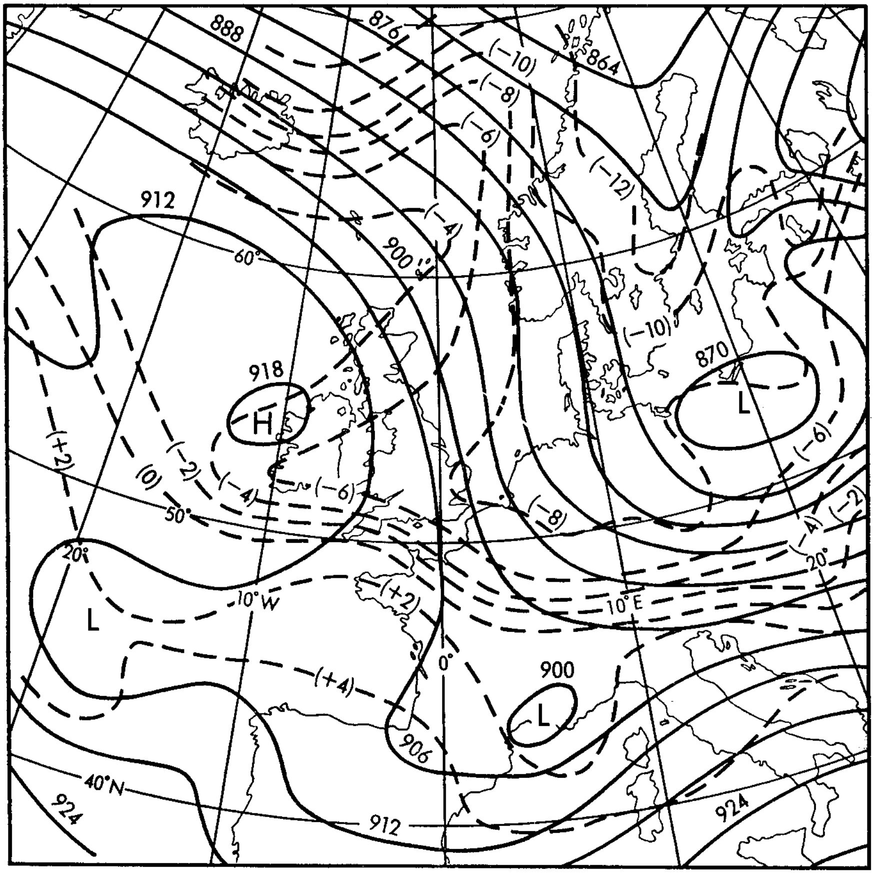

FIGURE 4—850 mb ISOTHERMS (DEGREES CELSIUS, PECKED LINES) AND 300 mb CONTOURS (DECAGEOPOTENTIAL METRES, FULL LINES) ON 28 APRIL 1976

Particularly good soaring conditions were observed where the cold tongue at 850 mb extended across East Anglia and the Midlands of England.

true for days when the longer flights occurred but not for shorter flights. Figure 5 shows the average 850 mb temperatures month by month for days on which cross-country flights took place compared with a 22 year average over the period 1956 to 1977.

During March, April and a number of days in May the temperatures on good soaring days were usually well below normal. In June, July and August, however, the temperatures were often above normal on days when shorter flights took place. These figures may have been biased by the unusually warm dry summer of 1976.

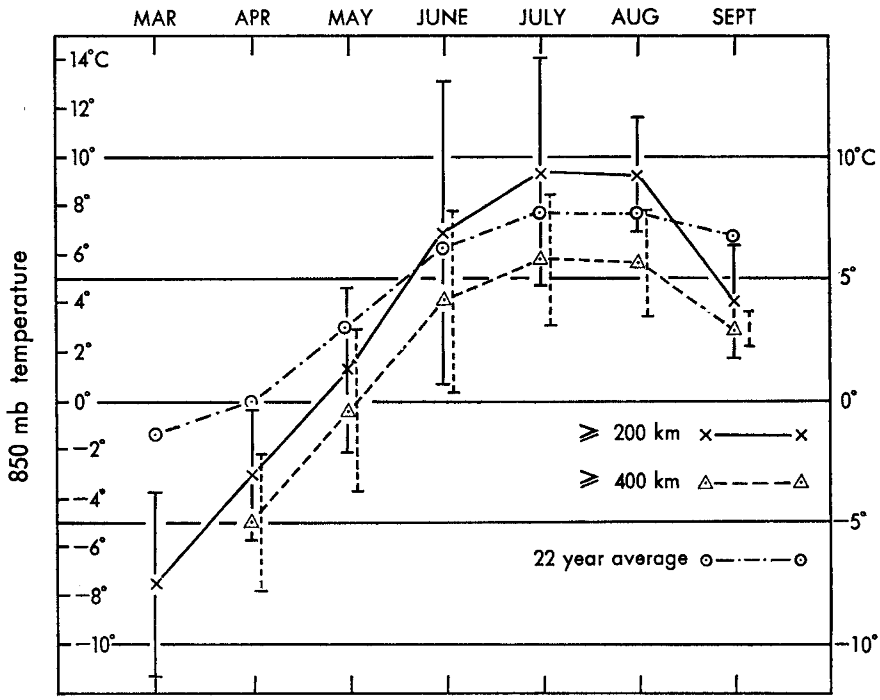

FIGURE 5—850 mb TEMPERATURES ON GOOD SOARING DAYS COMPARED WITH MONTHLY MEAN VALUES

The spread of values covered by one standard deviation is shown by bars. Those for the ⩾ 400 km days are slightly offset.

EXAMPLE OF CONDITIONS ON AN OUTSTANDINGLY GOOD SOARING DAY

Figure 6 shows the surface chart for 12 GMT on 28 April 1976 when conditions were unusually good; one pilot completed a 760 km triangle and three other pilots exceeded 500 km. The various features of the situation were classified as follows:

Previous trajectory of the air:	From the NE
Isobaric curvature over England:	Marked anticyclonic
850 mb wind at midday:	065° 14 knots
$\theta_{surface}$ minus θ_{850}:	4·5 °C
Dew-point depression at surface:	17 °C
850 mb temperature:	−7 °C (7 °C below normal)
Sunshine:	13·8 hours
Mean-sea-level pressure:	1027 mb
State of ground: Dry. Overnight rainfall:	Nil.
Total marks (combined assessment):	10

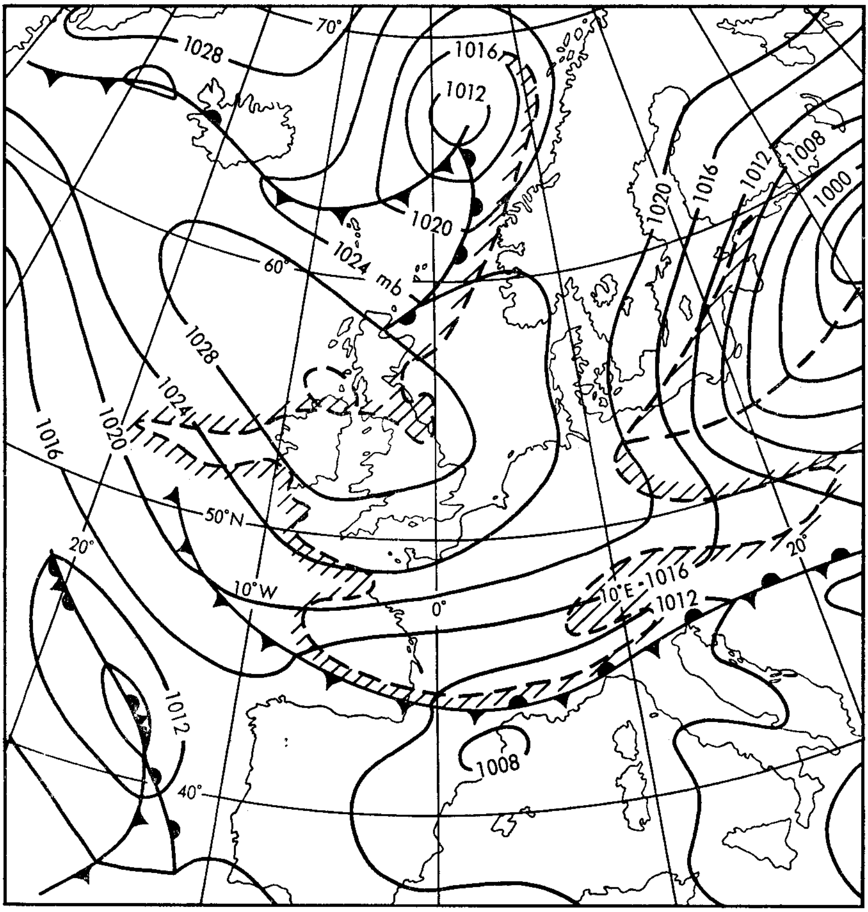

FIGURE 6—SURFACE CHART FOR 12 GMT ON 28 APRIL 1976

The pecked line with cross-hatching marks the boundary of major cloud masses seen on satellite pictures. Soaring conditions were outstandingly good over central and southern England.

SUMMARY OF CONDITIONS FAVOURABLE TO LONG CROSS-COUNTRY FLIGHTS OVER CLOSED-CIRCUIT ROUTES

Previous trajectory of air:	From NW, N or NE (never from the S).
Curvature of isobars:	Anticyclonic.
Mean-sea-level pressure:	1023 mb (plus or minus 7 mb).
850 mb wind:	Speed not more than 16 knots, direction between WNW and ENE through N.
Stability:	Potential temperature decreasing about 3 °C between the surface and 850 mb at time of maximum temperature. Depth of instability restricted by a stable layer below 700 mb sufficient to prevent any shower activity.
Surface dew-point depression:	11 to 18 °C by mid-afternoon.

Surface moisture and rainfall:	State of ground dry at 06 GMT, no overnight rainfall.
Sunshine:	At least 8 hours bright sunshine.
Visibility:	More than 20 km.

REFERENCES

BALL, F. K. 1960 Control of inversion height by surface heating. *Q J R Met Soc*, **86**, pp. 483–494.

BOOTH, B. J. 1978 On forecasting dry thermals for gliding. *Met Mag*, **107**, pp. 48–61.

BROOKS, F. A. and GODDARD, W. B. 1966 Observed four-component hourly energy balance. Davis, Cal., University of California, Department of Agricultural Engineering and Department of Water Science and Engineering. Grant No. DA-AMC-28-043-65-G12. Final Report, 1965, pp. 5–24.

GLAZIER, J., MONTEITH, J. L. and UNSWORTH, M. H. 1976 Effects of aerosol on the local heat budget of the lower atmosphere. *Q J R Met Soc*, **102**, pp. 95–102.

HIGGINS, H. C. 1963 The thermal index. *Soaring, Santa Monica, Cal.*, **27**, pp. 8–10.

KREIPL, M. 1976 Mit dem Wetter Segelfliegen. Stuttgart, Motorbuch Verlag, pp. 107–122.

LINDSAY, C. V. 1969 Air mass type and season favoring long cross-country soaring flights over the eastern United States. *Soaring, Santa Monica, Cal.*, **33**, pp. 14–20. (Also appears in *Schweizer Aerorevue*, **45**, 1970, pp. 81–85.)

MALPAS, W. E. 1977 Cross-country soaring weather in central France. *Sailpl Gliding*, **28**, pp. 98–99, 101.

MOFFAT, G. B. 1974 Winning on the wind. Los Altos, Cal., Soaring Press, p. 93.

RAYMENT, R. and READINGS, C. J. 1974 A case study of the structure and energetics of an inversion. *Q J R Met Soc*, **100**, pp. 221–233.

VENKATRAM, A. and VISKANTA, R. 1977 Radiative effects of elevated pollutant layers. *J Appl Met*, **16**, pp. 1256–1272.

WELCH, ANN, WELCH, L., and IRVING, F. 1977 New Soaring Pilot, 3rd edition. London, John Murray, p. 83.

REVIEWS

The versatile satellite, by Richard W. Porter. 245 mm × 145 mm, pp. viii + 173, *illus*. London, Oxford University Press, 1977. Price: £4.95.

In the eleven chapters of this book Richard W. Porter, an American aerospace expert describes a range of 'earth centred' satellite applications. He begins with two short chapters on the history and principles of satellite flight which are followed by a chapter describing the constraints imposed on designs by the environment in which the satellite must function.

The main part of the book (Chapters 4 to 10) describes the use of earth-orbiting satellites for communication, navigation, remote sensing of the atmosphere, the earth and its inhabitants, and astronomy. He concludes with two short chapters on manned flight and 'thoughts for the future'.

It is obvious from the wide scope covered in only 173 pages that the treatment cannot be detailed in any specific area. The author intends the book to be descriptive rather than mathematical and unlike the authors of some attempts at 'popular' treatments he succeeds in conveying information in a way that is readable and comprehensible without doing violence to basic physical concepts. In particular Chapter 2 entitled 'Overcoming gravity' gives a very simple yet accurate account of the way in which a satellite can be injected into orbit.

The part of the book of most direct interest to Meteorological Office readers should be Chapter 5 entitled 'Watching the weather'. Here a serious drawback of the book, also obvious in other chapters, becomes apparent: the discussion of current satellites is considerably out of date, extending only to about 1974. Despite this failing, this chapter contains useful descriptions of both imaging and temperature and humidity sounding techniques using visible, infra-red and microwave radiation.

Chapter 7 entitled 'Surveying the oceans and the land' contains a useful description of the capabilities of the first 'Landsat' Earth Resources Satellite. It includes some interesting images of south-east England on a remarkably cloud-free day in March 1973, illustrating the way in which information can be extracted from the various wavebands used.

In these cost-conscious times it is surprising, especially from an author who was the manager of the (American) General Electric Company's Aerospace Group, that no attempt is made in the book to evaluate the economic benefits of satellites. Perhaps this proved too difficult, or the book was written in more affluent times!

To summarize, this book is readable, informative and well presented both in text and photographs. It covers a wide area for such a short book and should be considered as general background reading about earth satellites. Used as an introduction to the subject it has a major drawback in having no references to more detailed texts. It also has a rather rudimentary index.

J. L. BROWNSCOMBE

Waves in fluids, by James Lighthill. 230 mm × 150 mm, pp. xv + 504, *illus.* Cambridge University Press, London, 1978. Price: £17.50.

In view of Professor Sir James Lighthill's reputation it is predictable that this review should be most favourable. Apart from personal satisfaction my efforts in reading have done little more than verify that the prologue by the author is accurate in terms of describing the contents and objectives of the book. It is intended for research workers concerned with wave motions in fluids as well as providing a text for courses at graduate and final year undergraduate level. The most striking aspect of the book is not the extent to which it reaches or explores research frontiers but the depth and thoroughness of the basic material. These fundamental ideas which are often assumed in texts with more specific applications are essential to a real understanding of waves in fluids.

The chapter headings 'Sound waves', 'One-dimensional waves in fluids' and 'Water waves and internal waves' should *not* be taken as implying a detailed discussion of these phenomena. Practical applications are fully indicated but within the chapters the main theme is of progressively developing fundamental ideas. These begin with non-dispersive waves for which the ideas of linearity and energy transport are introduced. Consideration is then given to the two limits of wavelength, that is to say sources small compared with wavelength and systems large compared with wavelength. Attenuation effects are also considered. The second chapter considers flows in ducts and then proceeds to non-linear effects in non-dispersive systems. Non-linear effects in dispersive systems are not considered in any detail although the prologue contains a brief introduction to this difficult field. The section on water waves enables dispersive systems and the idea of group velocity to be considered. The section on internal waves concentrates on internal gravity waves so as to enable a non-isotropic system in which group and phase velocities are in different directions to be considered. This is the extent of the basic material. The epilogue contains a brief but useful introduction to more advanced ideas including the combined effects of non-linearity and dispersion.

The book is thus not really for people wanting a brief outline of current ideas but is intended for those wishing to pursue matters in depth. The exercises given at the end of each chapter present some challenges and serve to illustrate the utility of the material presented. Owing to the clear physical interpretation much will be gained from the book by non-mathematicians but some sections will be opaque without experience with functions of complex variables and Fourier integrals.

In summary Professor Lighthill's book should become one of the standard works in fluid dynamics. It will be of value to all concerned with wave motion and meteorologists will form only a small part of the readership. The greatest benefit will go to students inasmuch as those already engaged in some research seldom find the time to give such a thorough but basic book the time it deserves.

P. J. MASON

NOTES AND NEWS

The Mk 3 radiosonde system is handed over

Friday 30 June 1978 marked the formal end of a long and often difficult road that started in 1958 with the decision to develop a new radiosonde system to replace the Kew Mk IIb. The Mk 3 radiosonde development ground station and the full, operational computer program for routine network stations was offered by Ferranti Computer Systems Ltd (FCSL) and accepted on behalf of the Meteorological Office by the Director of Services, Mr F. H. Bushby.

The Ministry of Defence Project Authority was the Directorate of Strategic Electronic Radar (DSLR), which was represented at the handover ceremony by Mr B. O. Penny, AD/SLR 3. Following the handover, a demonstration of the system was witnessed by the Ferranti and MOD personnel.

Operational stations have been converting to the new system at the rate of about one a month since February 1978 and the final station was converted in September 1978. The system is fully automatic and the standard TEMP messages are produced in near real time, fully coded and ready for dispatch from the radiosonde station to the telecommunication centre at Bracknell. (See Plates IV–VI.)

R. E. W. PETTIFER

Meteorological Magazine: price increase and change in page size

As from January 1979 the price of an issue of the *Meteorological Magazine* will be £1.30 and the annual subscription £16.74 including postage. The page size will be increased from Royal Octavo (246 × 156 mm) to Crown Quarto (246 × 189 mm).

OBITUARY

Mr J. C. Gordon

With the death on 19 August 1978 of Mr J. C. Gordon, Chief Meteorological Officer, Headquarters, Strike Command, the Meteorological Office has lost an outstanding military meteorologist and the Royal Air Force an able staff officer and a staunch friend. He had become widely known and respected by operational meteorologists in this country and overseas who will long remember him for his wisdom, tact, good judgement and humanity.

John Calder Gordon graduated at Edinburgh University, gaining an M.A. with honours in mathematics and physics in 1951. Earlier however, during 1946–48, his studies at the University had been interrupted by service in the Royal Air Force as a meteorologist. After forecasting training early in 1946 he received several postings as Pilot Officer and later Flying Officer, to airfields in eastern England. Subsequently he spent nine months at Air Headquarters in India, returning home in June 1948 for release from military service and the resumption of his studies. He rejoined the Office in 1951 as Scientific Officer and from the outset he made it known that he was interested in making his career in forecasting services and was not attracted by the opportunities in research that were then expanding. For a number of years he filled senior forecasting posts at major forecasting offices, notably at Prestwick Airport, London/Heathrow Airport, Malta and Nicosia (Cyprus). His ability as a forecaster was recognized in 1964 by his posting as Senior Forecaster in the Central Forecasting Office at Bracknell with promotion to Principal Scientific Officer.

In 1967 he resumed his association with the Royal Air Force on appointment as Chief Meteorological Officer at the Headquarters of the Far East Air Force in Singapore, where he quickly established the excellent working rapport with colleagues, meteorological and military alike, that was a hallmark of the staff and administrative work which he undertook in the remainder of his career. After a brief spell at Headquarters, Air Support Command, Upavon on his return to this country in 1971, he was selected to attend a course at the National Defence College. This led to further spells of Headquarters administration in the Defence Services and Central Forecasting branches at Bracknell. He reached the culmination of his career on appointment as Chief Meteorological Officer at Headquarters Strike Command in June 1976 with promotion to Senior Principal Scientific Officer. Rarely has a man been better suited by his talents, experience and personal qualities for his post.

Johnny Gordon had a huge capacity for making the most of life. A major pastime was golf and it was on the golf course whilst playing with friends and colleagues that he died. His great good humour was tempered with unselfishness and concern for others. As was said in a tribute by a U.S. Navy meteorologist at NATO, those of us who had the good fortune of serving and working with Johnny are richer by far for the experience. Our heartfelt sympathy is extended to his wife, Morag, herself a one-time member of the Office, and to his three children.

D. H. JOHNSON

THE METEOROLOGICAL MAGAZINE

NO. 1276 NOVEMBER 1978 VOL. 107

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, and marked 'For Meteorological Magazine'.

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1 monthly
Dd. 595890 K15 11/78

Annual subscription £13.14 including postage.
ISBN 0 11 724805 3
ISSN 0026–1149

Met.O.915
METEOROLOGICAL OFFICE

the meteorological magazine

DECEMBER 1978 No 1277 Vol 107
Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.915

THE METEOROLOGICAL MAGAZINE

No. 1277, December 1978, Vol. 107

551.501.45:551.521.1

THE DISTRIBUTION OVER GREAT BRITAIN OF GLOBAL SOLAR IRRADIATION ON A HORIZONTAL SURFACE

By J. P. COWLEY
(Meteorological Office, Bracknell)

SUMMARY

A set of linear regression equations between daily global solar irradiation and the duration of bright sunshine is solved for 10 stations in the United Kingdom which record both parameters, and the regression constants are estimated for 40 km square regions over Great Britain. Sunshine data from 132 stations distributed over Great Britain together with measurements of global solar radiation on a horizontal plane at a further 25 stations are used to estimate monthly averaged daily global solar irradiation on a horizontal plane, and a set of monthly maps is presented that shows the variation of this irradiation over Great Britain.

1. INTRODUCTION

A need exists for a knowledge of the variation of solar irradiation at the earth's surface over Great Britain: it is required for hydrological studies when calculating soil moisture deficits, and for building-science studies of the heat gains of buildings, as well as for other applied science studies.

Solar radiation (in the wavelength region 0·3–3·0 μm) is measured directly at only a small number of stations (see Figure 1), and it is therefore not possible to infer directly the irradiation over large areas of Great Britain. However, it is well known that the monthly global solar irradiation on a horizontal surface is closely related to the duration of bright sunshine (Ångström, 1924). In an attempt to describe the distribution of monthly averaged daily global solar irradiation over north-west Europe, Day (1961) used the relatively dense and uniform distribution of sunshine recording stations to estimate the irradiation, using the expression

$$G = G_0[a + b(n/N)], \qquad \ldots \quad \ldots \quad \ldots \quad (1)$$

where G is global solar irradiation,
G_0 is global irradiation above the atmosphere,
n is duration of bright sunshine,
N is maximum possible duration of sunshine, and
a, b are constants.

Day used the radiation data from 17 land stations in the United Kingdom and from 3 ocean weather stations and calculated regression constants *a*, *b* for each of them. Since *a*, *b* showed no simple pattern of variation he used the regression equation to estimate irradiation at sunshine stations in the vicinity of 11 'parent' radiation stations, using their values of *a*, *b*. He was thus able to calculate some 40 estimates that were reasonably uniformly distributed over the British Isles. The major limitation in Day's work was the restricted amount of data, poorly distributed, which was then available.

Collingbourne (1976) produced a set of five maps to illustrate the broad-scale seasonal and geographical variation in monthly averaged daily global solar irradiation over the United Kingdom measured on a horizontal surface. The set was based on solar radiation data alone, and the distribution of stations was close to that used by Day, but the data covered a much longer period. Subsequently, Caton and Smith (1977) have used the radiation data available to Collingbourne in combination with monthly maps of duration of bright sunshine over the United Kingdom (Meteorological Office, 1974), to produce, subjectively, a corresponding series of maps of solar irradiation. These maps contain greater detail than those of Collingbourne, showing such features as the lower levels of irradiation over mid-Wales and the higher ground of the English south-western peninsula that had been indicated more objectively by Day.

In the present work an attempt is made to relate daily global solar irradiation to duration of bright sunshine in an objective way, similar to that used by Day, but using more data, rather than in the more subjective manner of Caton and Smith. Values of the regression constants for 10 radiation stations (indicated in Figure 1) were calculated. It was found that they have both seasonal and geographical variations. Values of the constants were assigned subjectively to 190 square regions of 40 km side that cover almost all the land of Great Britain; these regions are those used by the Agricultural and Hydrometeorological Branch of the Meteorological Office in its computer-based evaporation model for which the constants may be of use when a form of Penman's equation is applied. The sunshine data for 132 stations were used to estimate global irradiation, using the value of the constants appropriate to the location of each station.

It is believed that the present work is superior to that of Day because

(a) more radiation and sunshine stations were considered,

(b) longer durations of measurements were available, and

(c) broad-scale patterns in the constants have been exploited.

It improves on the work of Caton and Smith because the sunshine data have been introduced in a more objective manner; the shapes of the patterns of sunshine distribution have still been heeded, however, on the assumption that the scale of variation of the constants was larger than the inter-station spacing.

2. RELATIONSHIP BETWEEN DAILY GLOBAL SOLAR IRRADIATION AND THE DURATION OF BRIGHT SUNSHINE

A correlation technique has been developed by the author to estimate the fractional daily global solar irradiation (G/G_0) from the average fractional duration of bright sunshine (n/N). It was found that an expression of the form of equation (1) applies well to partially sunny days, but sunless days form a

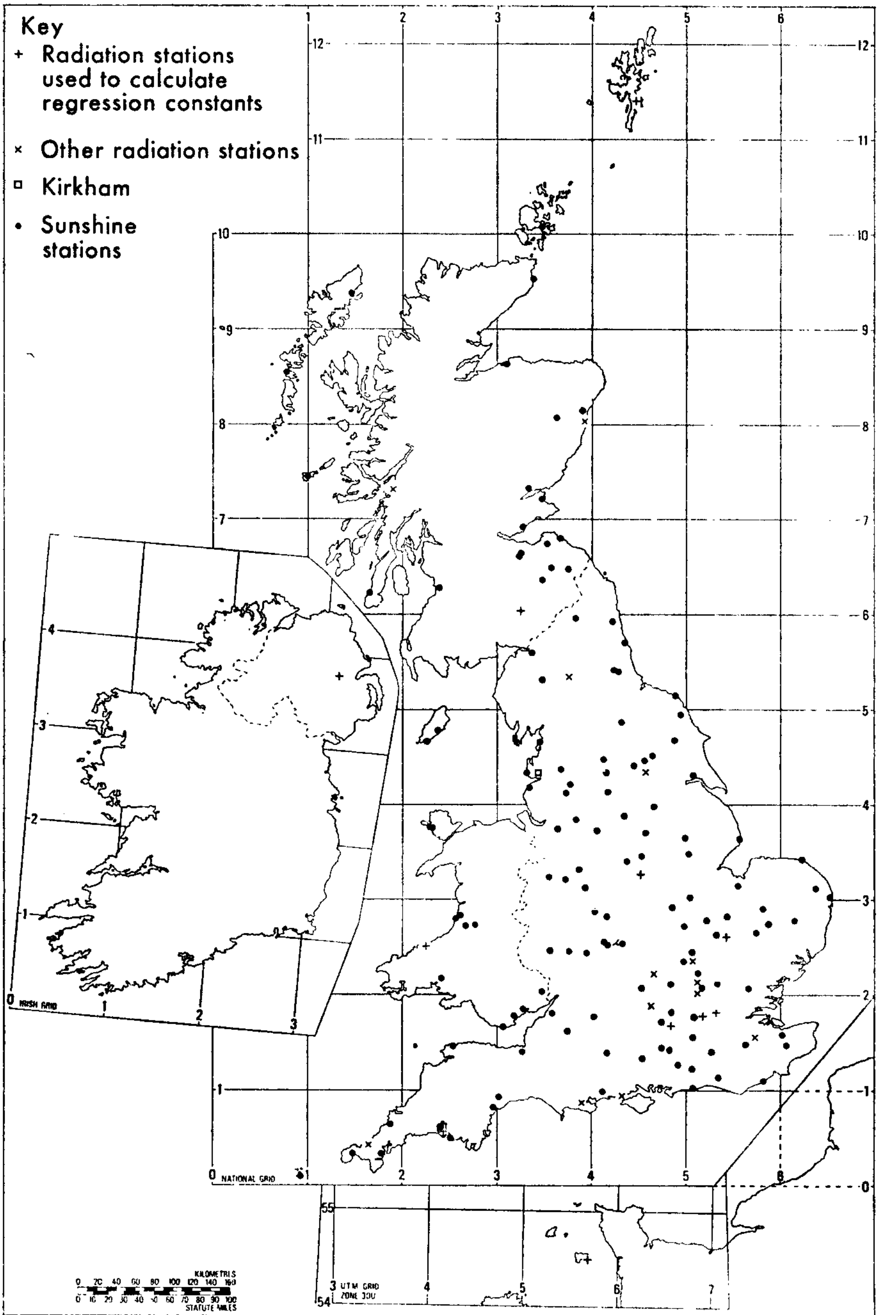


FIGURE 1—DISTRIBUTION OF STATIONS

separate population, being often associated with situations where multi-layered or thick clouds predominate, resulting in lower irradiations. Accordingly a modified equation was adopted:

$$(G/G_0) = \delta[a + b\,(n/N)] + (1 - \delta)\,a', \quad \ldots \quad \ldots \quad (2)$$

where $\delta = 0$ if $n = 0$,
$= 1$ if $n > 0$,
and a' = average value of (G/G_0) for sunless days.

In this work, (G/G_0) and (n/N) were calculated for each day; G_0 was based on the solar constant of 1353 W m^{-2}, correction being made for the eccentricity of the earth's orbit about the sun (Cowley, 1976), and N was taken as the astronomical day length allowing for average atmospheric refraction of the solar beam. A comparison of the application of equations (1) and (2) to the data for one station-month is shown in Figure 2(a).

It was shown that there is a lower root-mean-square deviation of data about equation (2) than about equation (1) for all months. This is illustrated in Figure 2(b).

3. Analysis

Values of a, a' and b were calculated for each of the 10 stations indicated in Figure 1, for the period 1966–75. This ten-year period was chosen as it is likely to exclude large-scale effects due to changes in atmospheric transparency that may be associated with the changeover from solid fuel to oil, gas and electricity for use in industry, commerce and domestic heating (see Cowley, 1976). It was, however, a sufficiently long period for accurate estimates of the values a, a' and b to be obtained, approximately 300 data-pairs being used for each station-month correlation.

It was found that a and a' are independent of season, having values of about 0·24 and 0·15 respectively varying geographically by $\pm$0·02 over the United Kingdom. The pattern of variation of a and a' is similar to the variation of annual average global irradiation in Collingbourne's maps. The geographical variation of b is less well defined but the values of b are seasonal, increasing from about 0·50 in the winter to about 0·55 in the summer, the geographical variation being $\pm$0·05 about the mean value. The geographical variations of the annual values of a and a' and of the June and December values of b are shown in Figures 3 (a)–(d).

As indicated in Section 1, values of a, a' and b were assigned to each of 190 square regions of 40 km side, covering almost all the land area of Great Britain, values of a and a' being constant through the year and values of b estimated for each month.

The reliability of the subjective assignment of values of a, a' and b to the 40 km squares was tested for Kirkham (53°48′N, 02°53′W) for which daily irradiation and duration-of-sunshine data were available on punched cards for a 5-year period. Kirkham is remote from any of the radiation stations for which values of a, a' and b had been calculated, being 150 km from Sutton Bonington (52°50′N, 01°15′W), 170 km from Eskdalemuir (55°19′N, 03°12′W), 240 km from Aldergrove (54°39′N, 06°13′W) and 215 km from Aberporth (52°08′N, 04°34′W). Values of a, a' and b for the 40 km square that encloses Kirkham

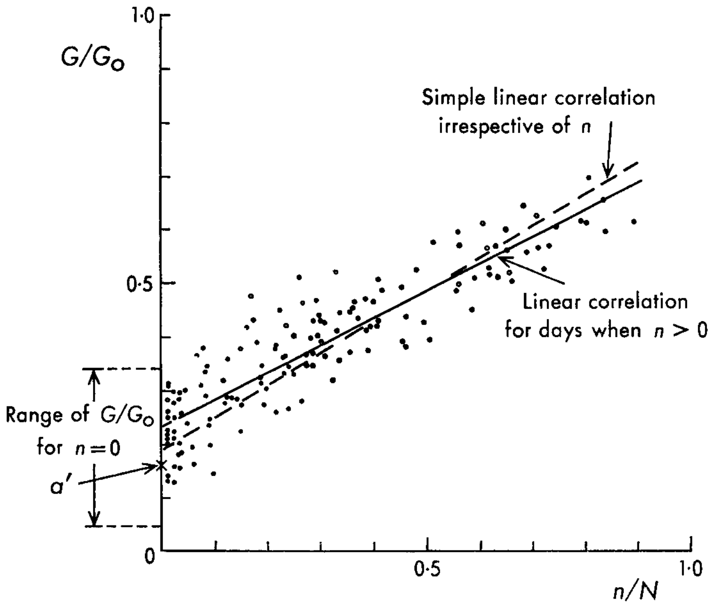


FIGURE 2(a)—COMPARISON OF TWO MODELS THAT RELATE GLOBAL SOLAR IRRADIATION TO THE DURATION OF BRIGHT SUNSHINE

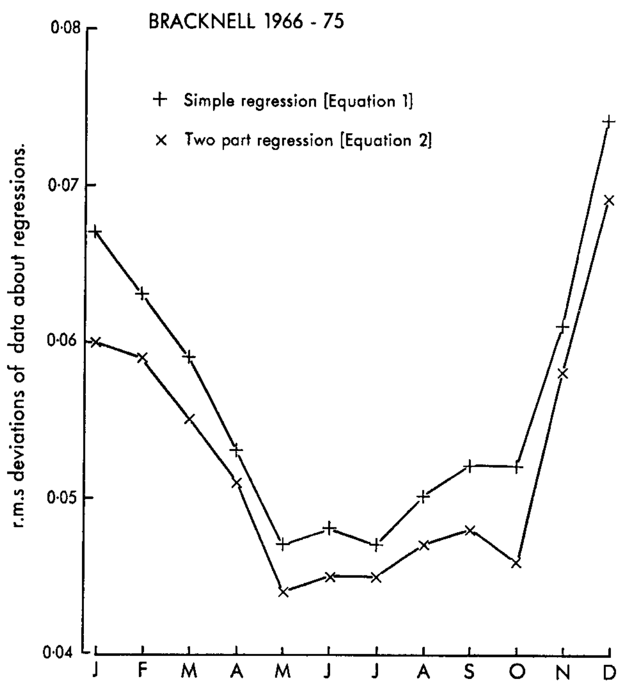


FIGURE 2(b)—ROOT-MEAN-SQUARE DEVIATIONS OF DATA ABOUT REGRESSION MODELS FOR EACH MONTH

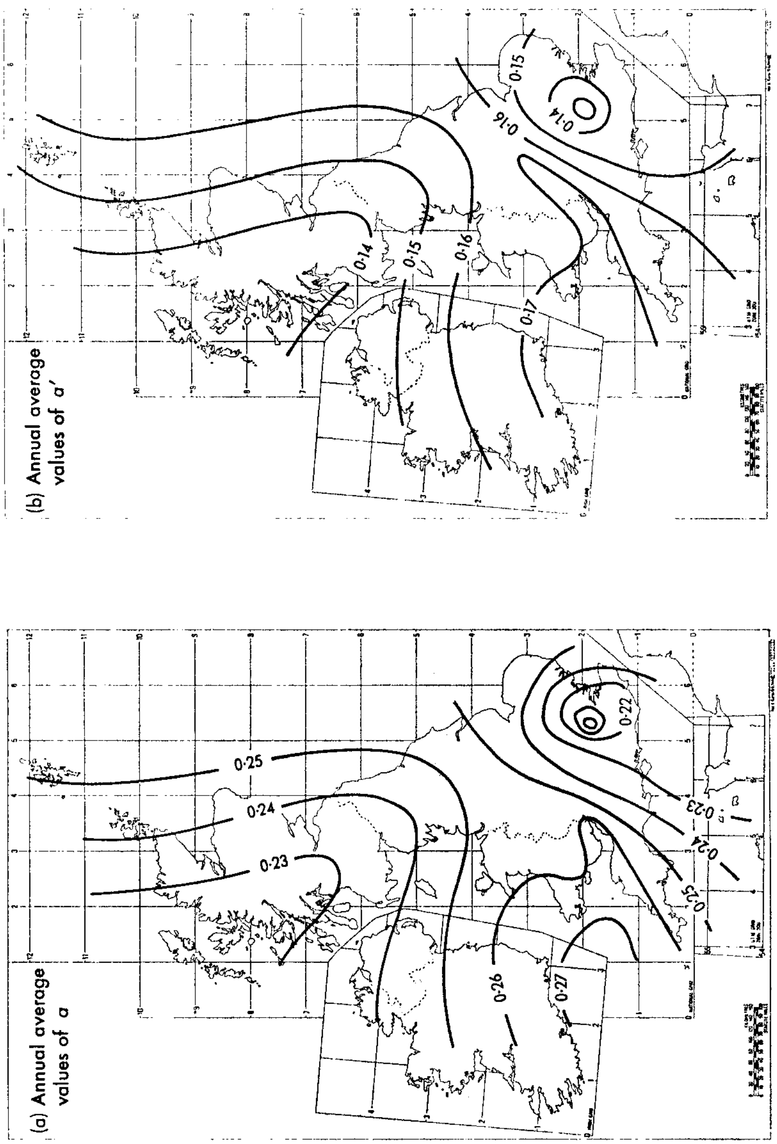


FIGURE 3—GEOGRAPHICAL VARIATIONS OF THE REGRESSION COEFFICIENTS

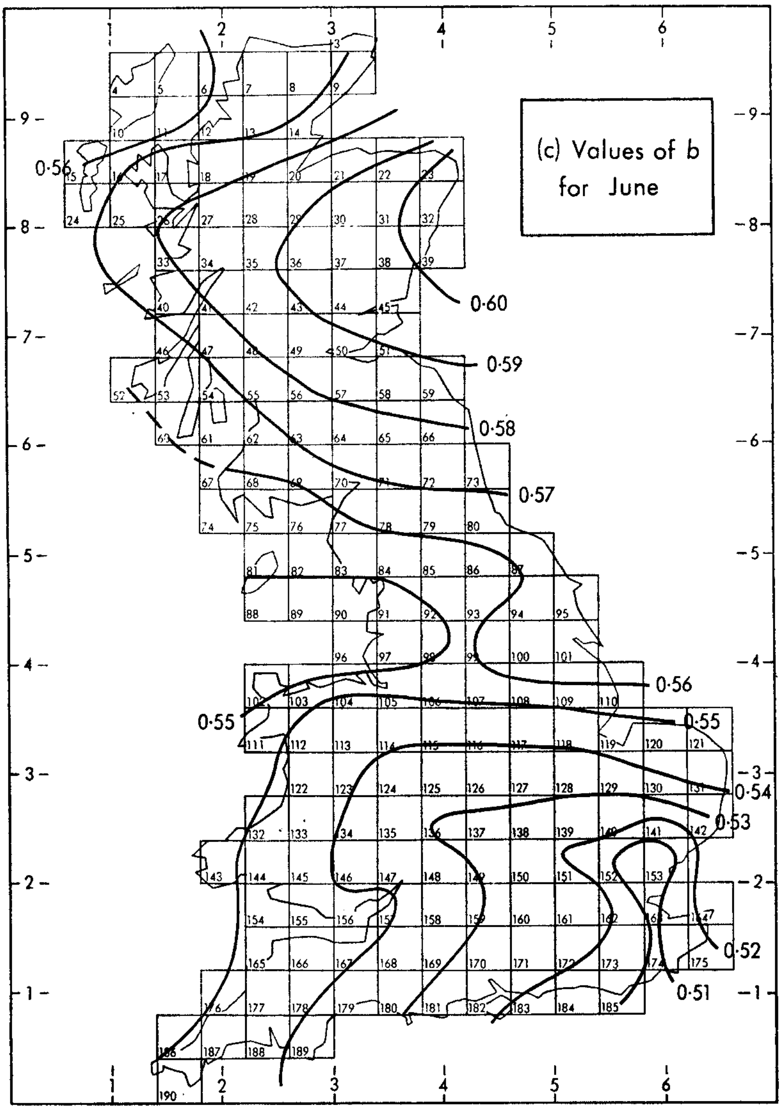


FIGURE 3—*continued*

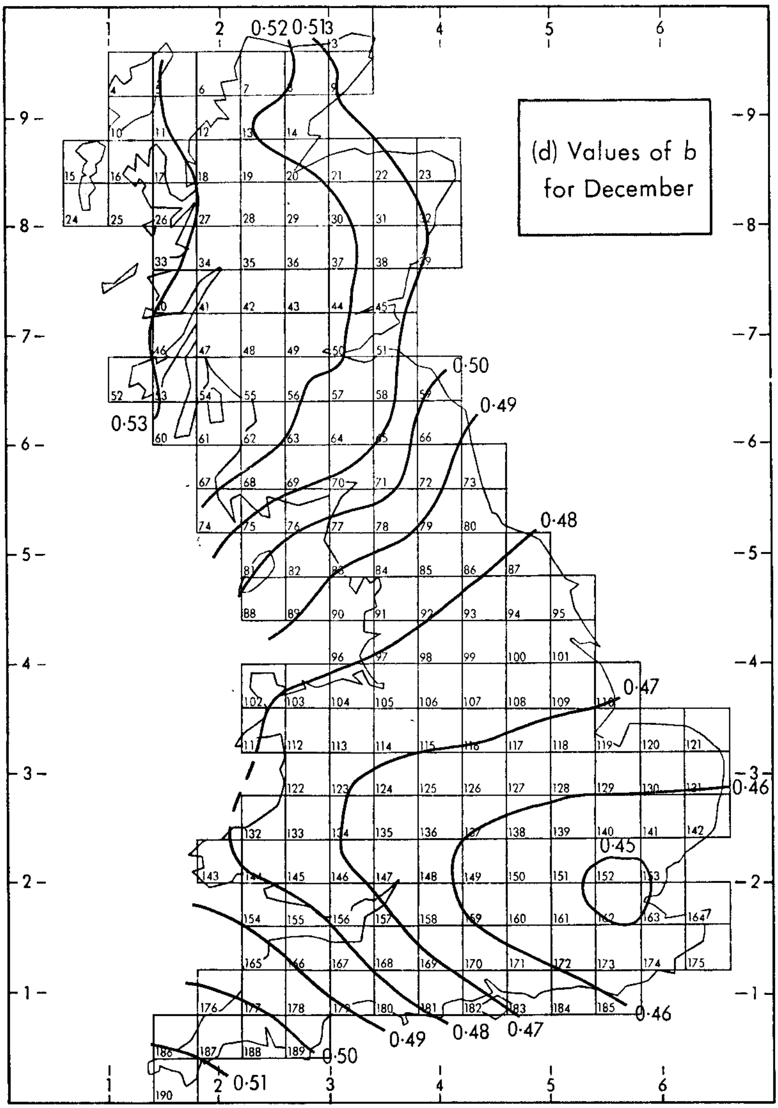


FIGURE 3—*continued*

were taken together with the sunshine data to estimate monthly global solar irradiations on a horizontal plane. The resulting correlation between predicted and measured irradiations is shown in Figure 4. Each point represents the data for a single month. The excellent agreement was taken as support for the validity of this work.

Only those stations whose sunshine data are available on computer magnetic tape were used to calculate estimates of global solar radiation in this work. The sunshine data for each of 132 stations were used to estimate the monthly irradiations from equation (2), using values of a, a' and b that apply to the square that encloses the station. A few stations (for example Tiree at 56°30′N, 06°53′W and Hastings at 50°51′N, 00°34′E) do not lie inside any of the 190 squares: values of the constants for these stations were estimates from the values assigned to the nearest squares.

Isopleths of equal irradiation were hand drawn both to the irradiations measured by stations indicated in Figure 1 and to those estimated by the procedure described here; the maps shown in Figures 5 (a)–(m) were thus obtained.

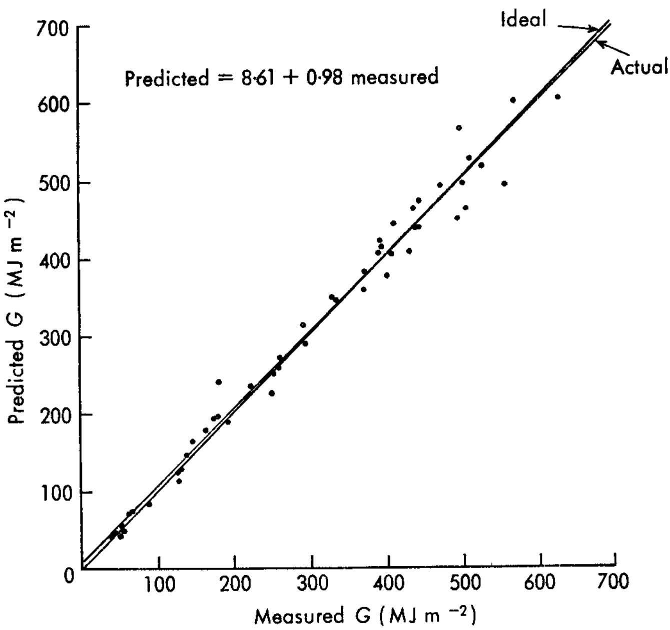


FIGURE 4—CORRELATION OF PREDICTED AND MEASURED MONTHLY GLOBAL SOLAR IRRADIATIONS FROM KIRKHAM, JULY 1968 TO DECEMBER 1973

4. DISCUSSION

The maps in Figures 5 (a)–(m) show the variation of global solar irradiation over Great Britain on a horizontal plane. It is seen that the pattern of isopleths shows three principal features:

(a) the general decrease in irradiation with increasing latitude: the seasonal change over Great Britain is less marked in summer than in winter as a result

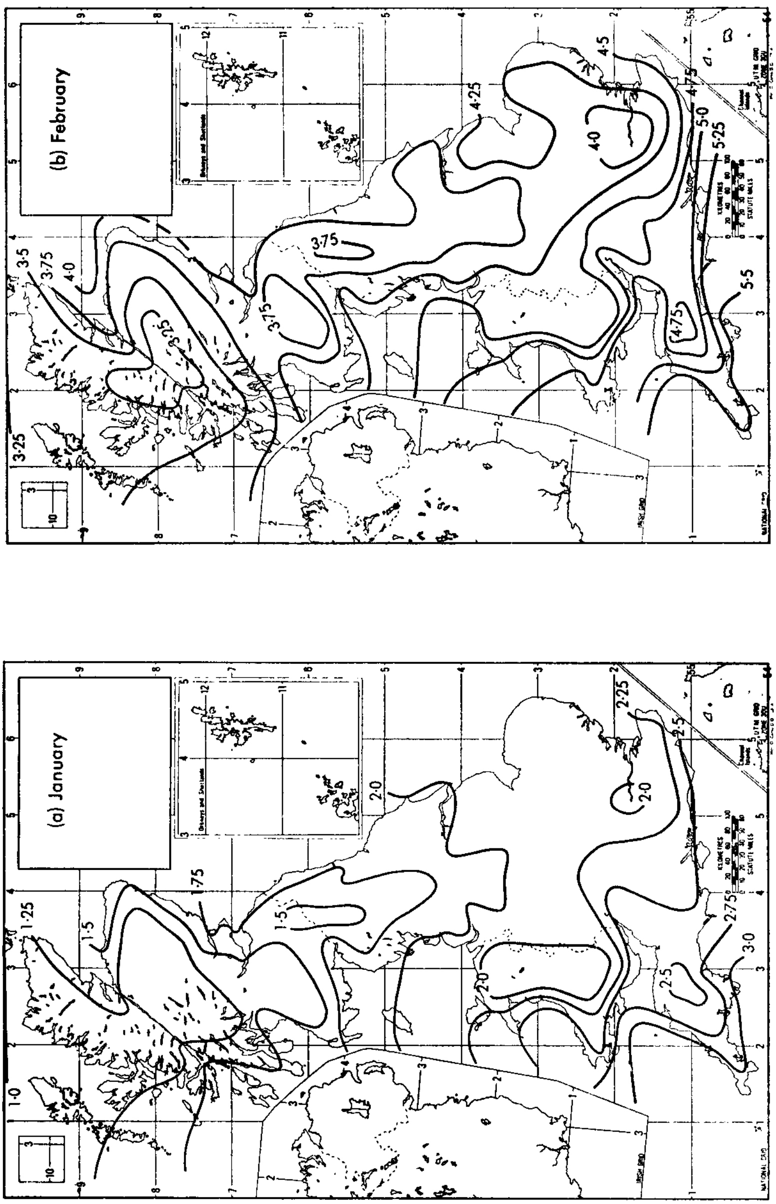
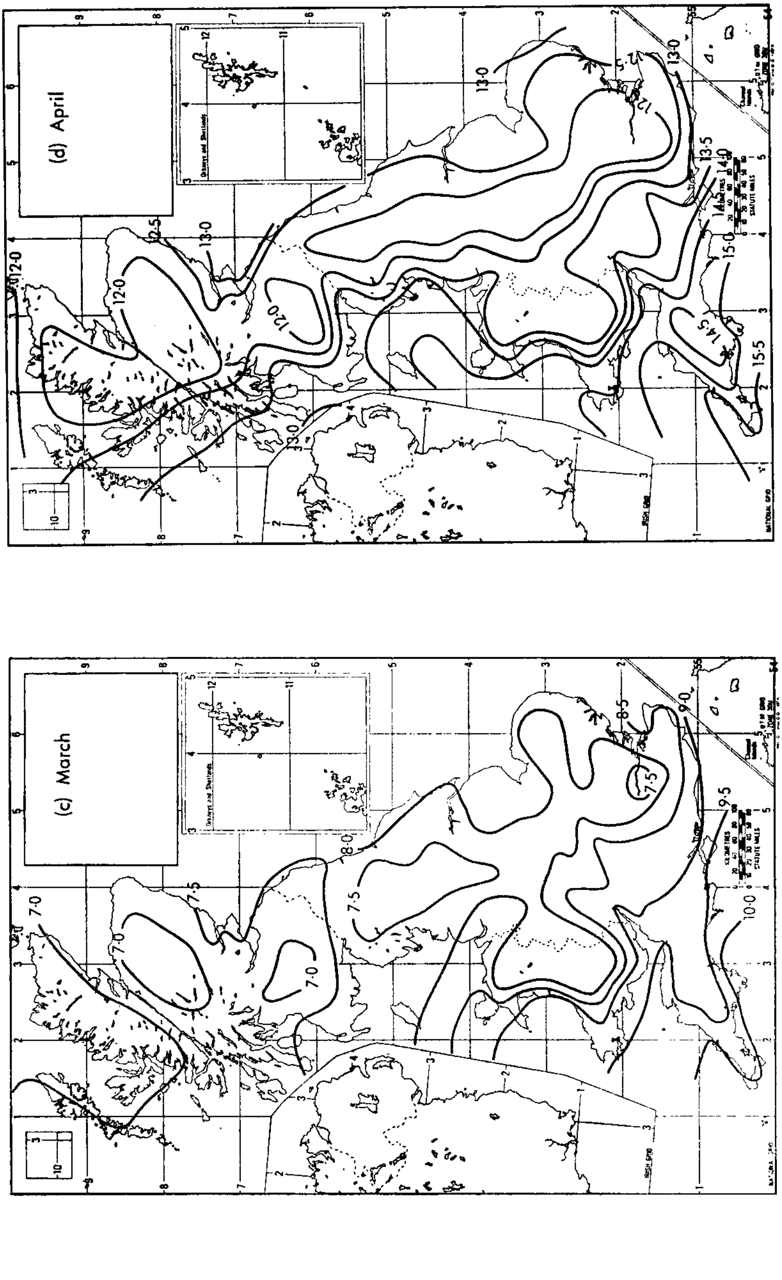


FIGURE 5—VARIATION OF MEAN DAILY GLOBAL SOLAR IRRADIATION OVER GREAT BRITAIN ON A HORIZONTAL PLANE



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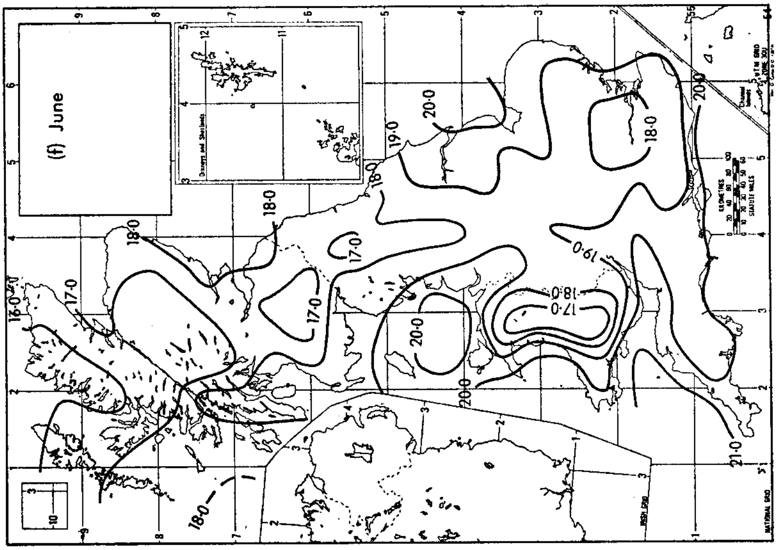

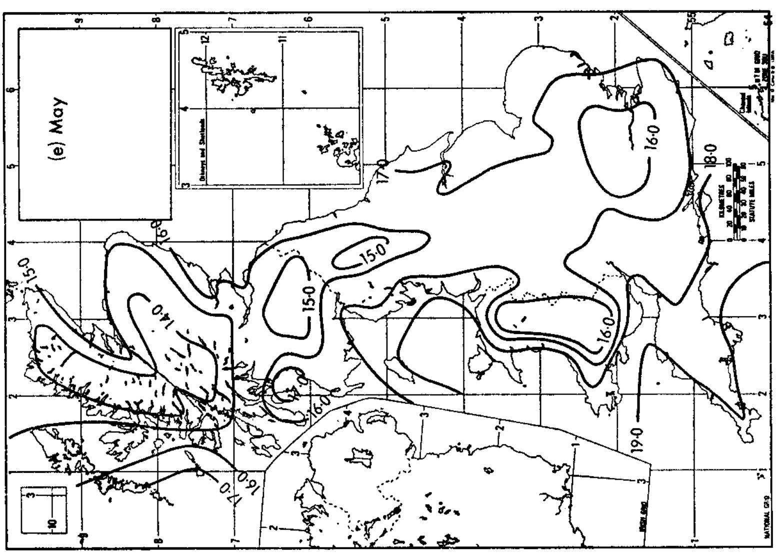

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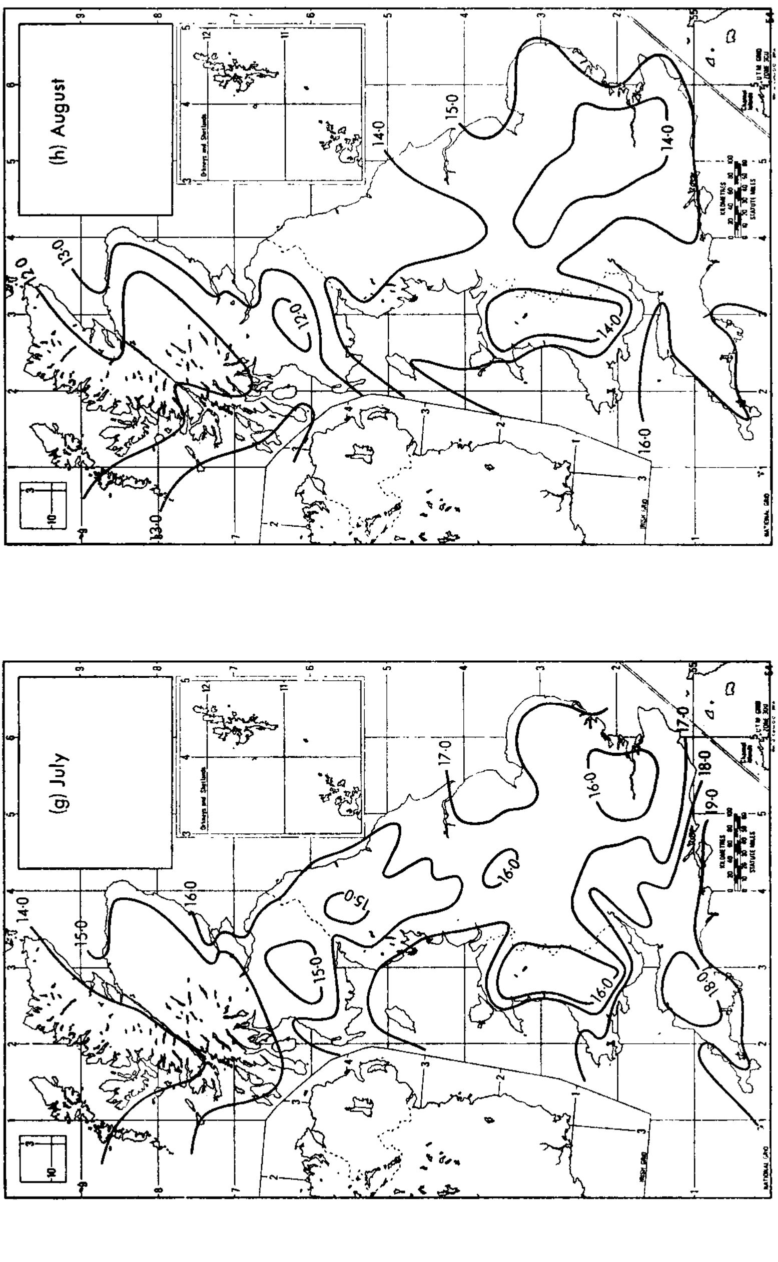

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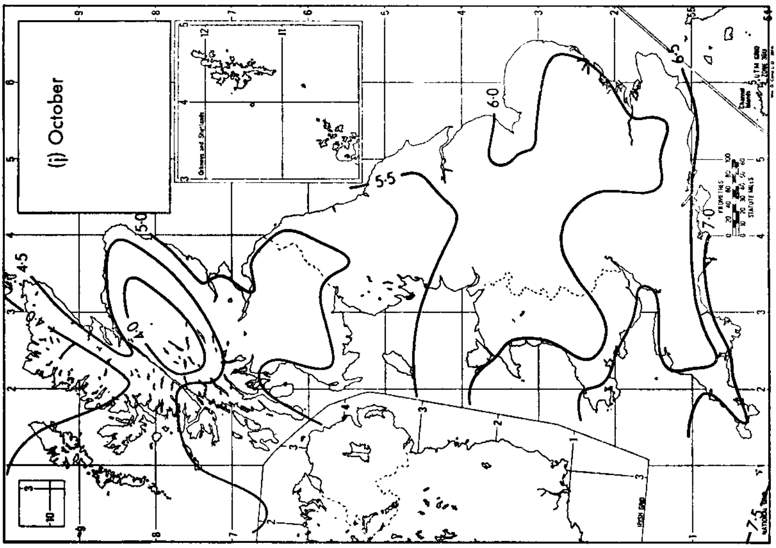

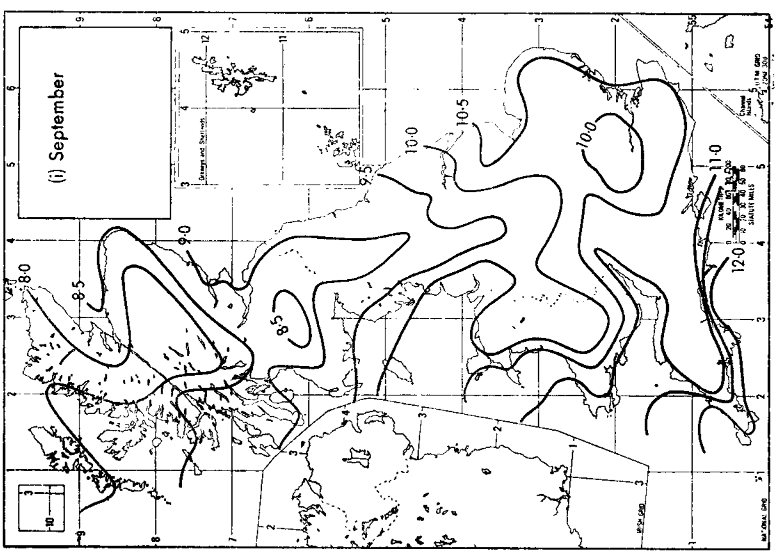

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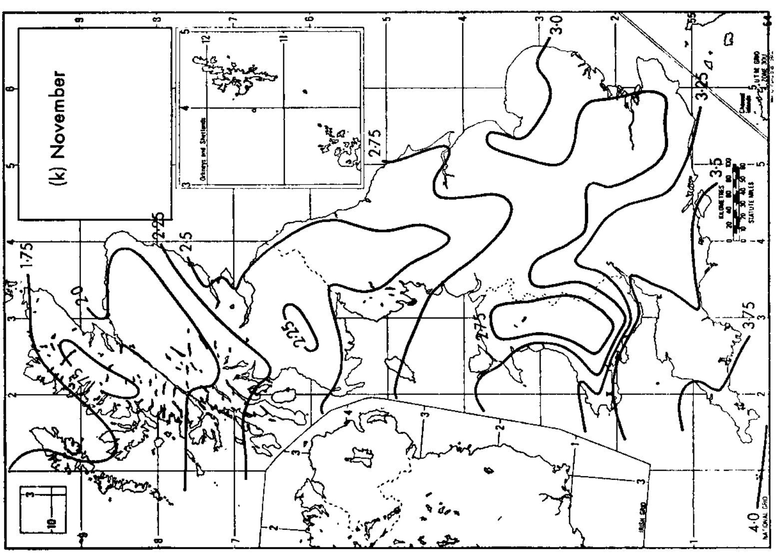

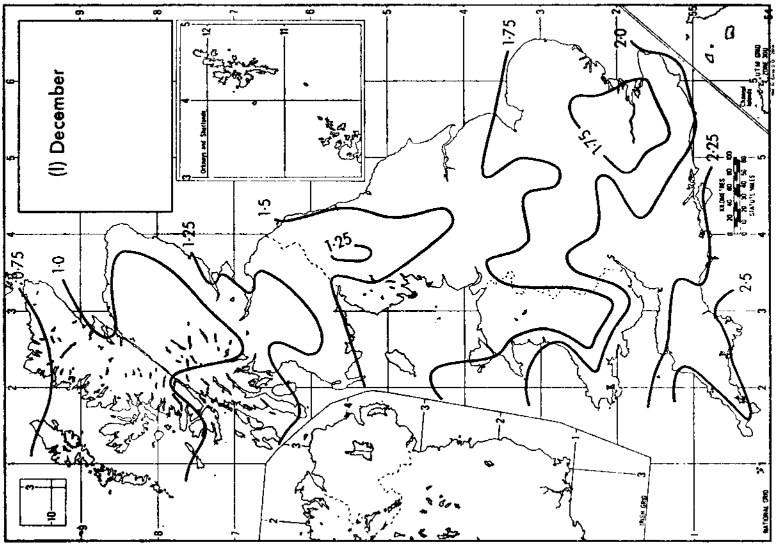

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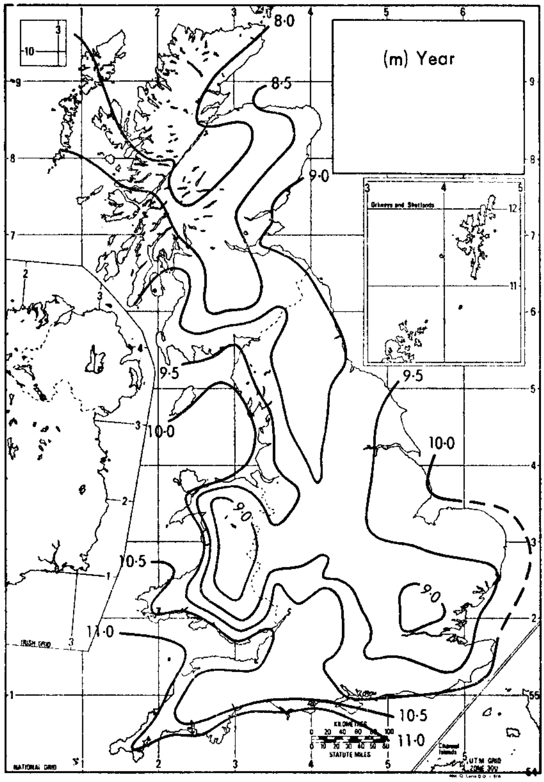

FIGURE 5—*continued*

of the longer days in the north compensating for the lower irradiances associated with greater solar zenith angles,

(b) the reduction of irradiation in inland areas associated with the increase in cloud amount, particularly over high ground, and

(c) the decrease in irradiation over a broad central area that covers the major conurbations.

The maps can only show the broad-scale features of the geographical variation; it would be erroneous to interpolate to high precision for particular locations, particularly those remote from radiation stations. The Meteorological Office has plans to enhance the distribution of recording equipment to monitor solar radiation: six radiosonde stations are to be equipped in the near future with MODLE 3 (Meteorological Office Data Logging Equipment) for this purpose and it is possible that global solar irradiation may be measured by up to 50 automatic weather stations located primarily in remote areas over the next 10 years. Only when these supplementary stations have been in operation for a decade will they be able to make possible a revision of the maps presented here. Until then little improvement is thought likely to be made.

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the meteorological magazine

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5. Conclusion

An improved correlation equation relating daily global solar irradiation to the duration of bright sunshine has been used to estimate the long-term monthly averaged irradiation from sunshine measured at a large number of stations. It has been shown that the technique of assigning correlation constants to 40 km squares over Great Britain works well for Kirkham, whose data were not used in deriving correlation constants.

Maps are presented which show the seasonal and geographical variation of global solar irradiation; little improvement is thought likely to be made until further radiation data become available.

6. Acknowledgements

The author gratefully acknowledges the help rendered by many people, including A. J. Ougham for his helpful discussions derived from his experience of the Campbell-Stokes sunshine recorder, and J. Arnott of the Agricultural and Hydrological Branch of the Meteorological Office for interpolating the correlation constants for the 190 square regions.

References

ÅNGSTRÖM, A. 1925 On radiation and climate. *Geogr Ann*, Stockholm, pp. 122–142.

CATON, P. G. F. and SMITH, C. V. 1977 Wind and solar radiation—availability in the United Kingdom. Presented at Conference on Ambient Energy in Building Design at the University of Nottingham, April 1977. To be published by the Construction Industry Conference Centre during 1978.

COLLINGBOURNE, R. J. 1976 Radiation and sunshine. Chandler, T. J. and Gregory, S. (editors), The climate of the British Isles, Longman, pp. 74–95.

COWLEY, J. P. 1976 Variations in global solar radiation at Kew. *Met Mag*, **105**, pp. 329–343.

DAY, G. J. 1961 Distribution of total solar radiation on a horizontal surface over the British Isles and adjacent areas. *Met Mag*, **90**, pp. 269–284.

METEOROLOGICAL OFFICE 1974 Maps of average duration of bright sunshine over the United Kingdom 1941–1970. (Unpublished, copy available in the Meteorological Office Library, Bracknell.)

551.509.329:551.596

A METHOD FOR THE PRODUCTION OF ACOUSTIC FORECASTS USING A DIGITAL COMPUTER

By R. T. SUGGITT
(Meteorological Office, Bracknell)

SUMMARY

Acoustic forecasting is a task that is performed operationally at three upper-air stations in the United Kingdom which provide meteorological support for Proof and Experimental Establishments and for military training ranges. These forecasts are currently done by hand, but the planned installation of minicomputers at these stations will allow the use of programs to produce, or to assist in the production of, acoustic forecasts. This paper discusses the background of this task, presents the approach that was taken in the development of an appropriate computer-based method, and describes the method itself.

INTRODUCTION

Three upper-air stations in the United Kingdom provide meteorological support for Proof and Experimental Establishments of the Royal Armament Research and Development Establishment, and for some firing ranges that are used for military training purposes. The staff at these stations are required, as a matter of routine, to make acoustic forecasts in order to predict the propagation of noise from gunfire and other surface detonations.

In some circumstances, if it is predicted that noise will be propagated towards populated or sensitive areas, firing will not commence; in others, particularly where training schedules may be disrupted, the forecasts are used in the retrospective verification of complaints and claims for blast-induced damage—for example the breakage of windows or other glass.

Normally these forecasts are done by hand, with data obtained from a recent radiosonde or pilot-balloon ascent, but the method involves a large amount of hand calculation and the production of a comprehensive forecast (that is to say for a full 360° about the firing point) is tedious and slow. In practice, therefore, the forecaster confines himself to the determination of what is known as the clear arc, and to the propagation of noise along a limited number of azimuths that are known to be sensitive. The clear arc is that set of directions towards which noise tends not to propagate.

In the near future these stations will be equipped with the new United Kingdom Mk 3 radiosonde system. In addition to the new radiosonde and new receiving and recording devices, each upper-air station will have a Ferranti Argus 700 E minicomputer. The details of the new hardware and of the computer software will not be given here: full accounts have been given by Hooper (1969) and Pettifer and Axford (1977) but some brief comments on the function of the minicomputer will be of value. This device is used during a radiosonde ascent to sample the coded data that are transmitted by the radiosonde, to apply quality control and calibration corrections to the data, to decode them, and to select from them the significant temperature and humidity values. The computer also interrogates a radar and uses the sets of azimuth, elevation, and slant range obtained to derive a wind profile for the ascent. The program that is provided for synoptic stations then uses those significant points and the wind profile to assemble a standard TEMP message, and a set of archives. It must be stressed that the only time the operators actually see the meteorological data is when the TEMP message is punched out on paper tape. The upper-air stations supporting Proof and Experimental Establishments and firing ranges must, in order to allow them to fulfil their operational commitments, be supplied with a data processing program that will print out meteorological data at appropriate intervals. In particular, the computer must be programmed to print out sufficient data to permit the production of acoustic forecasts.

While these data could simply be a set of values of temperature, humidity, and wind speed and direction, requiring that forecasts should still be done by hand, it is clear that the computer could, in addition, process the data to produce a forecast in either an intermediate or a final form.

Apart from the fact that staff will be released from the tedium of doing a large number of calculations by hand and may be employed in more productive tasks, this system has the advantage that forecasts may be produced more rapidly and in a more comprehensive form than is currently possible. The forecasts will benefit in any case from the improved accuracy of the new radiosonde.

Production of sound foci

A detonation of explosive on or near the surface creates a diverging shock wave, starting from the point of the explosion and spreading in all directions. In the hemisphere above ground the shock waves degenerate to sound waves quite rapidly, and the paths of the various parts of the wave front can be depicted by rays emanating in all directions from the centre of the explosion. These sound rays are then refracted through the atmosphere and may return to the surface at a point that is distant from the source, and if several such rays return to the surface in close proximity a focus is said to occur. The amount of energy that returns to the surface at a focus may be greater by some orders of magnitude than that which reaches the surface where there is no focus, and may, depending on the size of the original explosion, cause damage to structures.

The propagation of noise caused by large accidental explosions has been studied since the turn of the century, when it was correctly inferred that the variations of audibility were caused by variations of the wind and temperature structure of the troposphere and stratosphere. One such explosion was that in 1921 at Oppau in Germany, where, to the east, observers 220 km away heard the explosion whereas those 120 km away did not. Another was that at Burton-on-Trent, England, in 1944, an account of which is given by Murgatroyd (1944). The noise of the explosion, which involved 7000 tons of high explosive, was heard up to 150 miles (240 km) away to the south-east, but only up to 50 miles (80 km) away to the north-west. To the east there was a zone of silence between 70 and 100 miles (112 and 160 km) away, while the explosion was heard at locations outside and inside the zone.

In contrast, the amount of explosive detonated at Proof and Experimental Establishments or practice ranges is usually small. It is generally assumed that the amounts of energy transmitted into the middle and upper troposphere are insignificant for acoustic forecasting purposes, and that the position of foci and other features is determined by the wind and temperature structure of the lowest two kilometres of the troposphere (Jackson, 1971; Caton, 1971; Lumley, 1971).

This will allow for the production of an acoustic forecast for areas up to 40 km from an explosion. Jackson, Caton, and Lumley provide a useful insight into the problems that are encountered in operational acoustic forecasting, and into the procedures that are in use.

The classical theory of the refraction of sound is well established and will not be reproduced in this paper; it is similar in principle to the theory of refraction of light, which is probably more widely known. The behaviour of a ray of light at the boundary of two media is determined by the velocity of light within each medium. Similarly, the behaviour of a sound ray, travelling along a given azimuth from a point source, is determined by the velocity of sound in the layers of the atmosphere traversed. The velocity of sound in still air is proportional to the square root of the absolute temperature, thus the velocity of a sound ray travelling along a given azimuth is the algebraic sum of the velocity of sound due to the temperature and the component of the wind velocity along that azimuth.

Although this provides a useful intuitive starting point it is of no direct practical value because the lower troposphere does not exhibit a series of isothermal layers. Clearly some approximations are necessary to model a complex atmosphere, and to accommodate the way in which the atmosphere is sampled, but it is possible to derive a set of differential equations which are reasonably concise (Gilbert, 1961). These equations are then solved by means of an analog computer. Melville (1971) and Reed (1956) describe the way in which a variety of these devices are used.

Some constraints

It was clear that, if a model were to be devised for implementation on the upper-air station minicomputers, it would have to conform to a number of constraints. This model would have to become a part of the general radiosonde data processing program, and for reasons of economy would have to utilize the smallest area of core-storage possible. The model would have to be powerful and generalized because it would not be possible to involve the storage of, and reference to, a large number of set acoustic situations that could otherwise be used as precedents. To achieve this a 'first principles' approach is needed. A first principles approach would also obviate the need to program the forecaster's experience and the rules-of-thumb that tend to be used, which would themselves require a large area of core-storage and an excessive time for program development.

There are some advantages in using a digital computer, the most important being its large capacity for performing arithmetic calculations. There is no real penalty, therefore, if the model that is used requires a great number of calculations to be made, providing there are not so many that an acoustic forecast takes an excessive time to compute. This would be the case if it were attempted to use the differential equations that were devised for an analog computer, solving them by means of Runge-Kutta or similar methods.

One other small point that must be noted is that it was not necessary to devise a method that yielded results which were significantly better or more accurate than those given by the manual method, for the simple reason that the manual results are generally adequate for operational use.

The model

The best approach to the problem of calculating acoustic forecasting data was thought to be the provision of a program that calculated the range of return to the surface of sound rays, of varying initial elevations, travelling along azimuths of 10°, 20° . . . 350°, 360°. Those ranges, and tables of the velocity of sound at set heights, would be printed out for the forecaster who could then isolate the clear arc and areas where focusing was likely. It should also be possible for the forecaster to estimate the severity and persistence of any foci.

This system relieves the forecaster from the tedium of himself calculating ranges of return to the surface, but allows him to apply his experience to the interpretation of the computed results, and so retains much of the flexibility that was inherent in the purely manual method. In addition, it has the advantage that the considerable experience of the forecaster is retained, which will be of value if, for some reason, it is necessary to make an acoustic forecast when a computer is not available.

The model which is to be used has a framework that is similar to the manual method. The lowest 1950 metres of the atmosphere are considered as being divided into 13 layers, each 150 m thick. At each boundary a value of virtual temperature is obtained by interpolation from the two significant temperature points that overlap it, and a wind velocity is obtained by evaluating a mean wind within a 150 m layer that is centred on the given boundary.

It was found that, in order to achieve realistic results using 150 m layers, it was essential to consider the path of a sound ray as being curved. It was possible to assume a straight ray path if layers of 50 m were used, but this presents problems where wind evaluation is concerned, as the mean wind of a 50 m layer usually has a high 'noise' component.

It is possible to show (Gilbert, 1961) that a sound ray travelling along a given azimuth and traversing a layer of any thickness, but within which the sound velocity gradient is uniform, following a path that is an arc of a circle having its centre V_1/K below the layer, where

V_1 is the net velocity of sound at the lower boundary of the layer and

K is the sound velocity gradient within that layer.

This is illustrated in Figure 1.

Clearly this result may be applied if it is assumed that the sound velocity gradient within any 150 m is uniform. A method for acoustic forecasting based on this principle has been devised and tested, and has given results that seem reasonable, and comparable with those derived manually. A fuller description is given below.

Consider layer m that has a lower boundary m and upper boundary $(m + 1)$. A ray traversing this layer along a given azimuth will follow a path that is the arc of a circle with its centre D_m below boundary m, where

$$D_m = \frac{(V_m + A_m) \times \Delta h}{(V_{m+1} + A_{m+1}) - (V_m + A_m)},$$

and where

V_m is that component, along the given azimuth, of the wind velocity at boundary m,

A_m is the speed of sound in still air at boundary m,

Δh is the thickness of the layer (150 m).

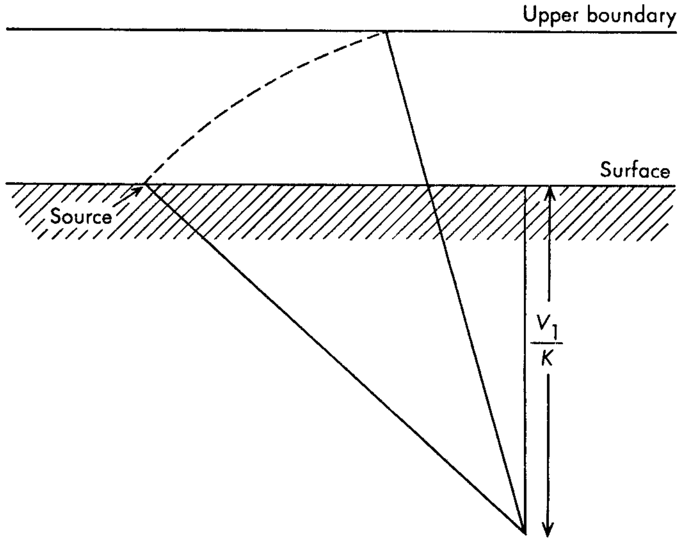

FIGURE 1—BEHAVIOUR OF A SOUND RAY, EMANATING FROM A POINT SOURCE, IN A LAYER WITH A SINGLE POSITIVE SOUND VELOCITY GRADIENT

Note that $A_m = 20{\cdot}05446\ \sqrt{T_m}$, where T_m is the absolute virtual temperature at boundary m, and V_{m+1} and A_{m+1} are defined as V_m, A_m for boundary $(m + 1)$.

The convention that then applies is that for a positive sound velocity gradient (i.e. if the sound velocity is greater at the upper boundary than at the lower), D_m is positive and the centre of curvature is below the lower boundary, so the ray curves downwards. If the gradient is negative, D_m is negative and the centre of curvature is above the lower boundary so the ray curves upwards. See Figure 2.

To trace the path of a sound ray along a given azimuth the following procedure is used. The lowest layer (layer 1) is considered, and the existence of a sound ray of initial elevation E_1 is assumed; it is possible then to calculate the elevation E_2 of the ray at its point of entry into layer 2, and the distance travelled (in a horizontal sense), ΔR_1. See Figure 3. This operation is repeated for layer 2, assuming that the elevation of the ray is E_2 and that the centre of curvature is D_2 below boundary 2, to calculate ΔR_2 and E_3.

This is continued for each layer in turn until the ray either becomes horizontal, escapes from the top layer, or attains an elevation greater than 20° and so cannot possibly return to the surface. If the ray becomes horizontal, when

$$D_i (1 - \sec E_i) \leqslant \Delta h$$

for some layer i, the range of return to the surface, R, may be evaluated as

$$R = 2 \sum_{m=1}^{i} \Delta R_m .$$

The ray tracing process is performed a number of times to give a comprehensive forecast for the azimuth under consideration. On the first occasion a ray

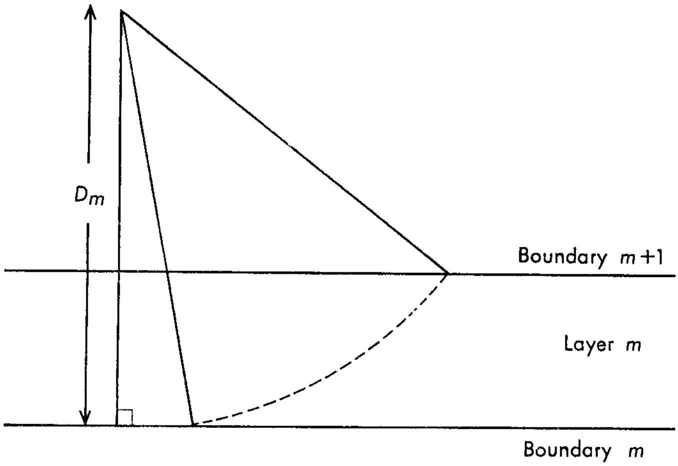

FIGURE 2—BEHAVIOUR OF A SOUND RAY IN A LAYER WITH A SINGLE NEGATIVE SOUND VELOCITY GRADIENT

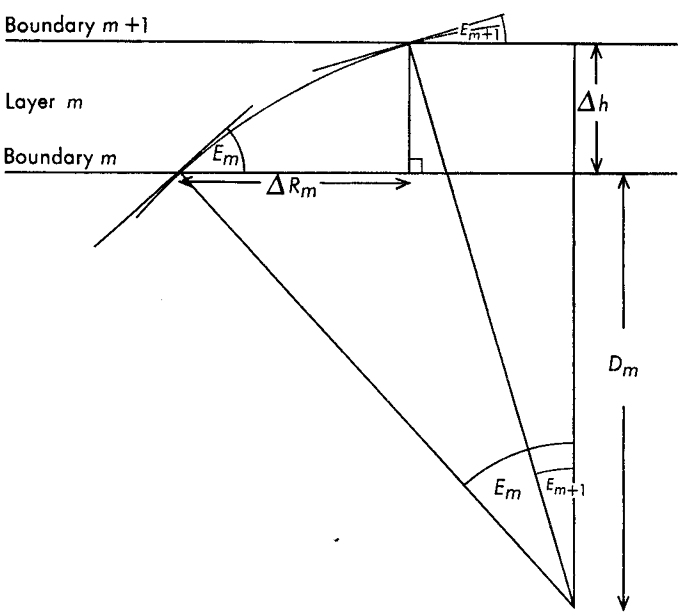

FIGURE 3—CALCULATION OF ELEVATION AT TOP OF LAYER, E_{m+1}, AND HORIZONTAL DISTANCE TRAVELLED, ΔR_m

having an initial elevation of 1° is taken. If it returns to the surface, a ray with an initial elevation of 2° is taken, continuing with rays of initial elevation of 3°, 4° etc., until a ray diverges from the surface (i.e. escapes from the top layer or attains an elevation of 20° or more). Finally, in order to provide a comprehensive forecast for a complete 360° of arc, the above procedure is performed for azimuths of 0°, 10°, 20°, . . . 350° in turn.

In order to add an illustration of the use of the model, an example of a typical radiosonde sounding is shown in Table I. Table II gives the model output which is set out in a similar manner to that which will be produced by the operational version.

TABLE I—WIND AND TEMPERATURE DATA FROM A RADIOSONDE ASCENT LAUNCHED AT BEAUFORT PARK AT 10 GMT ON 24 AUGUST 1977

Height above ground *metres*	Wind speed m/s	Wind direction *degrees*	Temperature °C
0	5·1	100	14·9
150	9·3	116	13·1
300	13·5	131	12·1
450	17·7	147	10·8
600	18·2	156	9·4
750	18·7	162	8·6
900	19·1	168	7·5
1050	19·7	175	6·3
1200	20·5	179	5·2
1350	21·7	182	4·4
1500	22·5	188	3·9
1650	22·1	202	5·2
1800	21·7	216	5·6
1950	21·2	229	5·6

REFINEMENTS

There are clearly a number of refinements that could be made to the model described above, some of which will be discussed here. They fall into two main groups, those that were not made because they do not appear to be operationally significant, and those that may be more easily performed by a forecaster.

Warren (1964) points out that the direction of travel of a sound ray is not the direction of the normal to the wave-front, which was an assumption made in producing the expression for D. The result quoted in the preceding section is therefore incorrect, the formula for D being more complex. However, in this application the error is small since only low elevation rays are involved, Warren's findings applying more to the propagation of noise from sonic boom and large (thermonuclear) explosions. This has been confirmed by a series of tests which show that, although the position of one or two ray returns is displaced by up to 1 km, the overall pattern of ray returns is unchanged.

Diamond (1964) explains techniques for determining the cross-wind effect on a sound ray, and by implication on the position of ray returns and foci. Cross-wind corrections were not made, however, because it was felt that the errors in the position of ray returns were small, and also because no such corrections are made in a manual forecast. It will be remembered that it was stated earlier that it was not intended to derive results significantly better than those which could be derived manually.

TABLE II—RESULTS GIVEN BY MODEL FOR RANGE OF RETURN OF SOUND RAYS

	Initial elevation (degrees)																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Azimuth (degrees)	*Range in kilometres*																	
10	1·2	2·4	3·6	4·8	5·9	5·2	5·1	5·3	5·5	5·8	5·6	5·8	5·9	6·2	12·9	23·2	27·6	—
20	2·2	4·5	6·7	7·6	5·9	5·7	5·8	6·1	6·1	5·9	6·0	6·1	6·3	10·3	15·4	21·0	23·6	—
30	21·7	10·2	7·8	7·0	6·8	6·9	7·1	6·5	6·4	6·4	6·5	7·9	10·2	13·4	17·1	21·7	21·7	21·1
40	10·6	9·5	8·9	8·8	8·0	7·3	7·1	7·0	7·0	7·2	9·5	11·4	14·1	16·1	19·9	20·7	19·4	18·5
50	10·7	9·8	9·1	8·6	8·3	8·1	8·1	9·0	10·0	11·4	13·1	15·3	15·9	20·1	20 0	18·9	17·3	18·0
60	11·2	10·7	10·3	10·6	10·8	11·1	11·5	13·0	14·2	15·6	15·8	18·7	21·1	19·4	17·6	16·4	15·8	17·1
70	14·6	14·5	14·5	14·7	15·0	15·7	16·4	16·2	16·4	20·4	22·4	19·5	17·9	16·4	15·7	15·4	15·8	17·4
80	18·5	18·1	17·9	17·7	17·7	20·9	23·0	21·9	20·4	19·9	17·4	16·3	15·6	15·1	15·2	15·2	16·0	17·1
90	24·1	23·4	22·7	22·1	21·6	19·9	18·5	17·5	16·7	16·0	15·5	15·0	15·0	14·9	14·8	15·6	16·1	—
100	17·2	18·8	18·3	17·8	17·3	16·8	16·3	15·8	15·6	15·3	15·1	14·9	14·7	15·2	15·4	—	—	—
110	17·6	17·3	17·0	16·7	16·4	16·1	15·8	15·5	15·3	15·1	15·2	15·3	15·3	—	—	—	—	—
120	17·3	17·0	16·7	16·4	16·1	16·0	15·9	15·8	15·7	15·6	—	—	—	—	—	—	—	—
130	17·6	17·3	17·1	16·8	16·6	16·4	—	—	—	—	—	—	—	—	—	—	—	—
140	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
150	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
160	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
170	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
180	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
190	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
200	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
210	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
220	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
230	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
240	7·8	15·7	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
250	1·8	3·7	5·5	7·4	—	—	—	—	—	—	—	—	—	—	—	—	—	—
260	1·1	2·2	3·2	4·3	5·4	14·2	—	—	—	—	—	—	—	—	—	—	—	—
270	0·8	1·6	2·4	3·2	4·0	4·8	7·2	9·5	—	—	—	—	—	—	—	—	—	—
280	0·6	1·3	1·9	2·6	3·3	3·9	4·6	6·0	7·2	—	—	—	—	—	—	—	—	—
290	0·6	1·1	1·7	2·3	2·9	3·4	4·0	4·8	5·6	6·3	12·5	—	—	—	—	—	—	—
300	0·5	1·0	1·6	2·1	2·6	3·2	3·7	4·2	4·8	5·4	5·9	8·6	—	—	—	—	—	—
310	0·5	1·0	1·5	2·0	2·5	3·1	3·6	4·1	4·4	4·9	5·3	6·3	7·5	—	—	—	—	—
320	0·5	1·0	1·5	2·0	2·5	3·1	3·6	4·1	4·3	4·6	5·0	5·4	6·3	7·0	—	—	—	—
330	0·5	1·1	1·6	2·1	2·7	3·2	3·8	4·3	4·3	4·6	4·9	5·3	5·8	6·3	—	—	—	—
340	0·6	1·2	1·8	2·3	2·9	3·5	4·1	4·3	4·4	4·7	5·0	5·3	5·6	6·0	6·3	—	—	—
350	0·7	1·3	2·0	2·7	3·4	4·0	4·7	4·4	4·6	4·9	5·2	5·4	5·6	5·9	6·2	—	—	—
360	0·8	1·7	2·5	3·4	4·2	5·0	4·7	4·7	5·0	5·3	5·5	5·5	5·7	5·9	11·0	38·7	—	—

Data in Table I are used as input. Dashes represent rays that do not return to the surface. Note the existence of a clear arc between 140° and 230°, the foci at about 15 kilometre range between 070° and 130°, at about 5 kilometres between 360° and 040°, and up to 5 kilometres between 260° and 350°.

The assumption that the sound velocity gradient within any layer 150 m thick is uniform may be questioned. It is agreed that the choice of 150 m layers represents a compromise between the use of a limited number of thick layers, for which meteorological data, especially representative wind data, may be obtained conveniently, and the use of a large number of thin layers for which the assumption is valid but for which it would be difficult to derive representative data. It may be preferable in some circumstances to use variable layers, choosing the height of the boundaries such that the sound velocity gradient within any layer *is* uniform. This is not possible for the situation here, however, because of the limitations in the area of core-storage that is available, and because the data selection programs would have to be particularly complex.

There are other reasons for not including the refinements mentioned previously. Murgatroyd (1944) explains that 'although the main characteristics of the sound propagation are determined by the wind and temperature variations with height, it would not be expected that the various zones of audibility would be well marked . . . the effects of scattering and diffraction . . . are likely to be considerable'.

In practice, therefore, it is not possible to predict the exact limits of areas in which a focus occurs, as the scattering and diffraction of sound rays (caused probably by mechanical turbulence) will blur them. Indeed, perhaps the word focus is something of a misnomer. Furthermore, when acoustic forecasts are made, they are generally expected to remain valid for up to three hours because the state of the atmosphere does not normally change markedly in this period, and also because of the great difficulties that would arise if forecasts had to be produced at shorter intervals. Within a two to three hour period, however, small changes do occur in the temperature and wind structures, owing to the natural spatial and temporal variability of the atmosphere. It is accepted that a forecast can only be valid in general terms, and that the position of the clear arc and any foci are only approximate, assuming probable errors of about $\pm 10°$ and ± 2 km respectively.

It is clear then that the value of additions to the model which attempt to improve its accuracy is very limited.

Other refinements were not made to the model because it was thought that they were best left to a forecaster. One of these is known as skipping, or the formation of multiple reflections. This occurs when the attenuation of noise at a focus is low, which tends to happen if a focus is formed at a water surface. The focus can, in this situation, act as a secondary source and create an additional set of foci, which would result in the noise of a explosion being carried for many kilometres. Other refinements not included are the calculation of overpressures associated with foci, the effect of an undulating terrain on the position of foci, and the limits of what Murgatroyd calls the audibility bowl (the area within which a grazing sound ray is available).

Conclusion

It is hoped that this paper has provided an adequate summary of the theoretical problems that apply to acoustic forecasting, and of the method that will be used when the Mk 3 radiosonde comes into service at the upper-air stations providing support for Proof and Experimental Establishments and practice ranges.

The use of a ray-tracing approach, in which the path of each ray in each layer is considered, will readily accommodate multi-gradient atmospheres, and so will eliminate some of the approximations that have to be made manually when multi-gradient atmospheres occur. It is impossible, however, to estimate how valuable this and other potential improvements are when forecasts are made operationally for periods of up to two or three hours. The natural spatial and temporal variability of the atmosphere is usually the dominant factor in this period.

It is certain, however, that the forecaster will be spared the tedium of making a large number of calculations by hand, which should allow him to concentrate primarily on the task of interpreting the simple results printed out by the computer. It should therefore be possible in the near future to make acoustic forecasts more rapidly and in a more comprehensive form, which will, it is hoped, be of benefit both to the official establishments and to the public at large.

References

CATON, P. G. F. 1971 Acoustic forecasting. London, Min Def CSR(A), *Instr Serv Tech Note* 1/71, pp. 103–104.

DIAMOND, M. 1964 Cross wind effect on sound propagation. *J Appl Met*, 3, pp. 208–210.

GILBERT, G. H. 1961 An approach to the quantitative production of anomalous blast effects. *J Appl Met*, **1**, pp. 102–106.

HOOPER, A. H. 1970 Some features of the new United Kingdom radiosonde. Geneva, WMO. Upper-air instruments and observations, WMO No. 284, pp. 364–377.

1970 Problems in the automatic computation of radiosonde data. Geneva, WMO. Upper-air instruments and observations. WMO No. 284, pp. 347–363.

JACKSON, F. C. 1971 Acoustic forecasting at P & EE Shoeburyness. London, Min Def CSR(A), *Instr Serv Tech Note* 1/71, pp. 105–111.

LUMLEY, P. D. 1971 Noise problems on Salisbury Plain. London, Min Def CSR(A), *Instr Serv Tech Note* 1/71, pp. 121–122.

MELVILLE, S. 1971 Background notes on the use of a purpose built computer to aid acoustic forecasting at AWRE Foulness. London, Min Def CSR(A), *Instr Serv Tech Note* 1/71, pp. 113–120.

MURGATROYD, R. J. 1944 The audibility of the Burton-on-Trent bomb dump explosion. (Unpublished, copy available in the Meteorological Office Library, Bracknell.)

PETTIFER, R. E. W. and AXFORD, D. N. 1977 A new, fully automatic radiosonde ground-station for use with the United Kingdom Mk 3 radiosonde. WMO Technical Conference on Instruments and Methods of Observation (TECIMO), Hamburg 1977, WMO No. 480, pp. 19–24.

REED, J. W. 1956 Weather determines blast prediction for atom tests. *Weatherwise*, **9**, pp. 202–203.

WARREN, C. H. E. 1964 A note on the refraction of sound in a moving gas. *J Sound Vib*, **1**, pp. 175–178.

REVIEW

A meteorological study of July to October 1588: the Spanish Armada storms (*Research Publication* No. 6), by K. S. Douglas, H. H. Lamb and C. Loader. 295 mm × 210 mm, pp. 76, *illus.* Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, 1978. Price: £2.85 plus postage and packing.

The stormy weather which had such an adverse effect on the Spanish Armada in 1588 is described and interpreted in a sequence of synoptic weather charts for the period. Although the interpretation is sometimes open to serious doubt especially near the western edge of the charts, the central parts of the analyses appear generally well-founded. The reader can form an opinion on each chart by consulting the extensive table of weather reports. This table also includes the authors' interpretation of the reports in terms of synoptic situations.

The interpretation of various features, such as sea fog and preferred frontal positions, in terms of atmospheric and oceanic circulations which could have been typical of the 'Little Ice Age' is interesting and feasible. Unfortunately the reviewer finds the Scandinavian cold front on Figure 9, mentioned in this context, to be rather speculative, but other charts mentioned seem better founded. The discovery of Tycho Brahe's records for Denmark is of great value for our knowledge of late 16th century climate.

The variable v_G in the two equations on page 9 should be the observed warm sector surface wind over the ocean. If it were the gradient wind then in equation (ii) V_y would always exceed 0·6 × the gradient wind and would not be only half the gradient wind as stated in the text. Table 4 is consistent with the use of surface wind in the equations.

The study will be of interest to historians and meteorologists and has helped to improve our understanding of the climate of North-west Europe in the late 16th century.

D. E. PARKER

NOTES AND NEWS

Launch of the United States operational weather satellite, TIROS-N

TIROS-N, the first of the third generation of United States polar-orbiting operational meteorological satellites was launched from the Western Test Range, California on 13 October. Whilst these satellites will, like their predecessors, provide cloud imagery and measurements of atmospheric temperature structure, improved instruments and an extended range of measurements should provide significant improvements in the quality of these products. For instance, the instrumentation for determining temperature structure comprises an infra-red radiometer with a spatial resolution of about 20 km which has 20 spectral channels, a 3-channel stratospheric radiometer, and a 4-channel microwave radiometer, which together should lead to an improvement in the accuracy of temperature retrievals particularly in the presence of cloud. The payload also includes a telecommunication package which will locate and collect messages from the constant level balloons and drifting buoys being deployed in conjunction with the First GARP Global Experiment.

For the first time instruments provided by the United Kingdom and France are being used on a United States operational meteorological satellite. The United Kingdom's contribution is the Stratospheric Sounding Unit (SSU) provided by the Meteorological Office. This is an infra-red radiometer which will provide information on a global scale about the temperature structure in the stratosphere at heights between 25 and 50 km. Its observations are processed in Washington in conjunction with data from two other radiometers on the satellite to provide the routine atmospheric temperature profiles. The SSU data are also transmitted to the Meteorological Office where they are processed and used for research purposes.

The design of the SSU is based on the principle of 'selective chopping' exploited by Oxford, Reading and Heriot Watt University instruments on earlier United States experimental satellites. The experience gained has made the United Kingdom a leader in this field and was the main reason for the selection of the SSU as part of the TIROS-N instrument package. The SSUs have been developed and manufactured by Marconi Space and Defence Systems at Frimley. Some of the most critical components, the detectors, were made at Plessey's Allen Clark Research Centre, Caswell.

OBITUARY

We regret to record the death of Mr H. M. Keenan, Port Meteorological Officer in Glasgow, on 8 July 1978.

Mr Keenan, who was born and educated in Glasgow, joined the ocean weather ship service of the Meteorological Office as 3rd Officer in April 1969 after more than 25 years' experience as a merchant navy officer with Anchor Line and in the coastal trade between Scotland and Ireland. He was promoted to established 2nd Officer the following December and thereafter sailed frequently as Acting Chief Officer. In March 1972 he was appointed Port Meteorological Officer in Glasgow, where he remained until his death. He will be remembered for his lively sense of humour as well as for his devotion to duty.

We record with regret the death on 5 September 1978 of Miss A. M. Peters, Assistant Scientific Officer, of the Agriculture and Hydrology Branch.

Miss Peters joined the Office in September 1944 and worked in a number of outstations and Headquarters branches.

THE METEOROLOGICAL MAGAZINE

NO. 1277 DECEMBER 1978 VOL. 107

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NOTICES

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1 monthly **Annual subscription £13.14 including postage**

Dd. 595890 K15 12/78

ISBN 0 11 724806 1
ISSN 0026–1194