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Variations in the onset of the Indian south-west monsoon and summer circulation anomalies

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Summary

Anomaly circulations in April and May over India associated with the late onset of the summer monsoon at eight locations in India have been obtained by using correlation techniques. Regression equations using significantly correlated winds in April and May have been developed to forecast the dates of onset at the eight locations. Onset forecasts for the central parts of the country appear to be reasonably good.

1. Introduction

The mean dates of the onset of the south-west monsoon over India, and their variability, trends and periodicities were studied by Subbaramayya *et al.* (1984, 1987, 1988). The circulation changes preceding the onset of the monsoon were examined by Maung Tun Yin (1949), Sircar and Patil (1962), Ramamurthi and Keshavamurthy (1964), Pant (1964), Wright (1967), de la Mothe (1968), Ananthakrishnan (1970) and Kuettner and Unninayar (1981). The important changes found over India are (a) westward displacement of an upper trough in the subtropical westerlies from 90° E to 75° E, (b) northward displacement of the subtropical anticyclone over the Arabian Sea, and (c) establishment of an anticyclone over Tibet and an easterly jet over peninsular India. It is also suggested that, if the above circulation changes occur early or late, accordingly there would be changes in the onset of the monsoon.

Investigations have been made of the correlations of some meteorological parameters spread widely over the globe in April and May with the seasonal monsoon rainfall in attempts to forecast the monsoon rainfall using highly correlated antecedent factors. Similarly, attempts were made (Kung and Sharif 1981) to forecast the date of the onset over the Kerala State coast in the extreme south-west of peninsular India. No satisfactory study of the circulation anomalies in April and May with the onset in different parts of the country have been made so far. The authors have therefore studied the correlations of the onset dates with the winds in April and May at different levels at eight locations. From this the anomaly circulations associated with delayed monsoons were obtained. Regression equations to forecast the onset dates using significantly correlated wind parameters were also obtained.

2. Data and analysis

The eight locations selected were Trivandrum, Madras, Visakhapatnam, Bombay, Nagpur, Calcutta, Lucknow and New Delhi, the locations of which are shown in Fig. 1. The monthly mean winds in April and May at 700, 500 and 300 mb at these locations for the period 1959–88 were obtained from *Monthly climatic data for Indian stations* published by the India Meteorological Department.

Onset dates at these eight locations for the period were obtained from estimates of the position of the

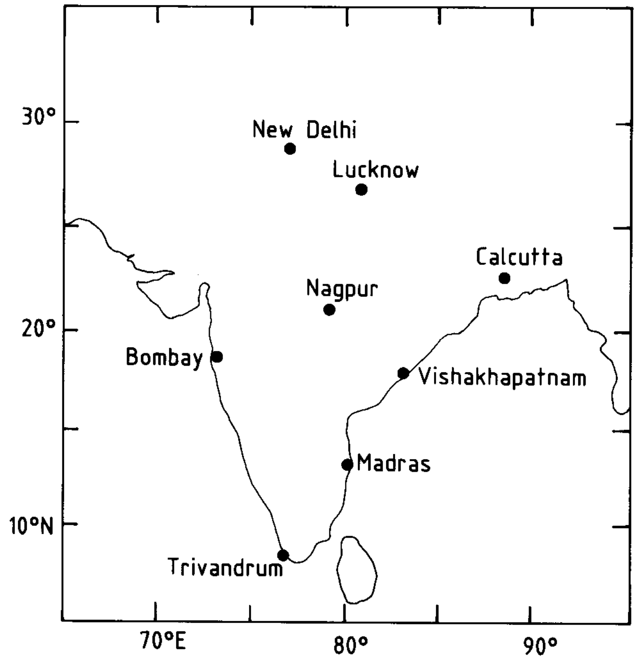

Figure 1. Locations mentioned in the text.

northern limit of the monsoon prepared each day during the period of the advance of the monsoon, following the procedure described by Subbaramayya and Bhanu Kumar (1978). The onset dates are reckoned from 1 May, thus an onset date of 5 June is taken as day 36.

Correlations between the onset dates at each location and the zonal and meridional winds at the above three levels at all eight locations were evaluated. To obtain the anomaly circulations related to the delayed monsoon at any location, the standard deviations of both zonal and meridional components of winds at the eight locations were first multiplied by the respective correlation coefficients. These values were then vectorially combined and the results were plotted and streamlines drawn at each level. Anomaly winds were plotted by the standard shaft and barb method.

The nature of the anomaly patterns relative to the mean circulations were studied. Keeping the consistency of the anomaly patterns in view, the wind parameters with the highest correlations were chosen to develop regression equations for forecasting the onset date at each location. However, the correlations at Lucknow

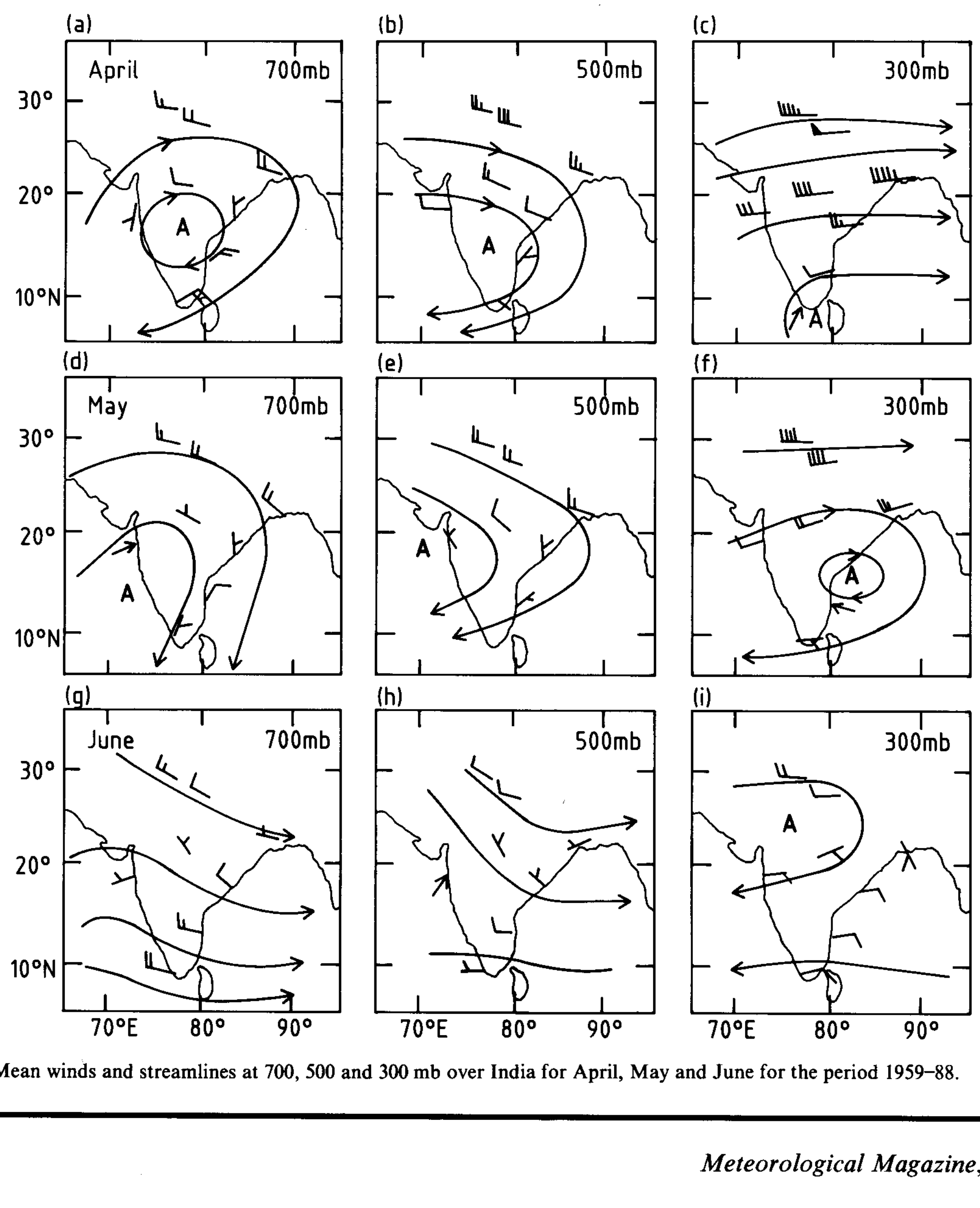

Figure 2. Mean winds and streamlines at 700, 500 and 300 mb over India for April, May and June for the period 1959–88.

were not considered when developing regression equations because the wind data in some years were missing. However, the available winds were also plotted to examine the consistency of the anomaly circulations. The significance of the regressions were examined by the Student's t-test.

3. Results and discussion

3.1 Mean circulations in April, May and June

The mean circulations over India at different levels in April, May and June are shown in Fig. 2. In April at 700 mb there are west-north-westerlies over northern India and north-easterlies over the north peninsula with an anticyclone in between. At 500 mb there are strong westerlies over northern India but the north-easterlies over the south of the peninsula are weak. The subtropical ridge in between is situated at relatively low latitudes. At 300 mb the westerlies over northern India are stronger than at lower levels and have extended to the north peninsula. The subtropical ridge is thus situated more to the south at this level. While at 500 mb the subtropical anticyclonic cell is over the west Arabian Sea and the peninsula, at 300 mb it is over the south of the Bay of Bengal. The above features indicate a general northward decrease of temperature throughout the troposphere and relatively higher temperatures in the south Bay of Bengal than over the south Arabian Sea in the upper troposphere.

In May the circulation features are essentially similar to those in April but the winds are relatively weaker and the axis of the subtropical ridge is more nearly vertical. This indicates that the meridional temperature gradient in the more southerly latitudes has weakened considerably. However, temperatures east of the peninsula are higher than those to the west.

In June there are strong westerlies over the south of the peninsula in the lower troposphere whose strength decreases with height, while easterlies prevail in the upper troposphere. Over northern India there are westerlies throughout the troposphere and they are relatively strong in the upper troposphere. The subtropical ridge is situated over northern India. These features indicate a reverse temperature gradient over southern and central India. The zonal wind shear in the lower troposphere shows considerable cyclonic vorticity over southern and central India and anticyclonic vorticity over northern India. In the upper troposphere over the entire region there is anticyclonic vorticity.

3.2 Circulation anomalies associated with the delayed monsoon at different locations

Trivandrum. The circulation anomalies in April and May associated with the delayed monsoon at Trivandrum, evaluated by the procedure described in section 2, are shown in Fig. 3(a). In April there is (a) cyclonic anomaly over the north-east of the peninsula and the adjoining north-west Bay of Bengal throughout the troposphere, and (b) north-easterly anomaly over north India in the middle and upper troposphere. This means that the normal westerlies over north India are more meridional and the anticyclonic circulation over eastern India and the west Bay of Bengal is weaker.

In May there is a significant anticyclonic anomaly over the south-west of the peninsula and the south-east Arabian Sea in the lower and middle tropospheres and a cyclonic anomaly in the middle and upper tropospheres over north-west India and anomalous westerlies in the upper troposphere in the extreme south. It is interesting to note that in the extreme south the easterlies are stronger in the lower troposphere and weaker in the upper troposphere than is the normal in May. Also, the anomalous circulation in the upper troposphere over the north-west Bay of Bengal and the adjoining land area shifts to north-west India by May.

Madras. The anomalous circulations related to the late onset at Madras are shown in Fig. 3(b). In April there is cyclonic circulation in the lower troposphere over the north-west Bay of Bengal and the adjoining parts of eastern India. In the middle and upper troposphere there are north-easterlies over north India and easterlies over the peninsula. These anomalous circulations are similar to those associated with the delayed monsoon at Trivandrum. In May also there is a significant anticyclonic anomaly in the lower and middle troposphere over the south-west of the peninsula and the east Arabian Sea as in the case of Trivandrum, but there is no cyclonic anomaly in the higher levels over north-west India.

Bombay. The anomalous circulations associated with delayed monsoons at Bombay are shown in Fig. 3(c). In April there is anticyclonic circulation throughout the troposphere over the west peninsula and it is particularly pronounced in the middle troposphere. The anomaly winds in May show an anticyclonic circulation across the centre of the peninsula in the lower troposphere and cyclonic circulation in the middle and upper troposphere over north-west India.

Visakhapatnam. The anomaly circulations (Fig. 3(d)) show anticyclonic circulation in the lower troposphere which shifts westward with height. Northerly anomaly over central India is strong, particularly in the upper troposphere. In May there is a ridge extending from the south-west peninsula to north-east India in the lower troposphere. There is a trough over north-west India which is quite pronounced in the middle and upper troposphere.

Nagpur. The anomaly circulations are shown in Fig. 3(e). In April there is a strong anticyclonic circulation over the central west peninsula in the lower

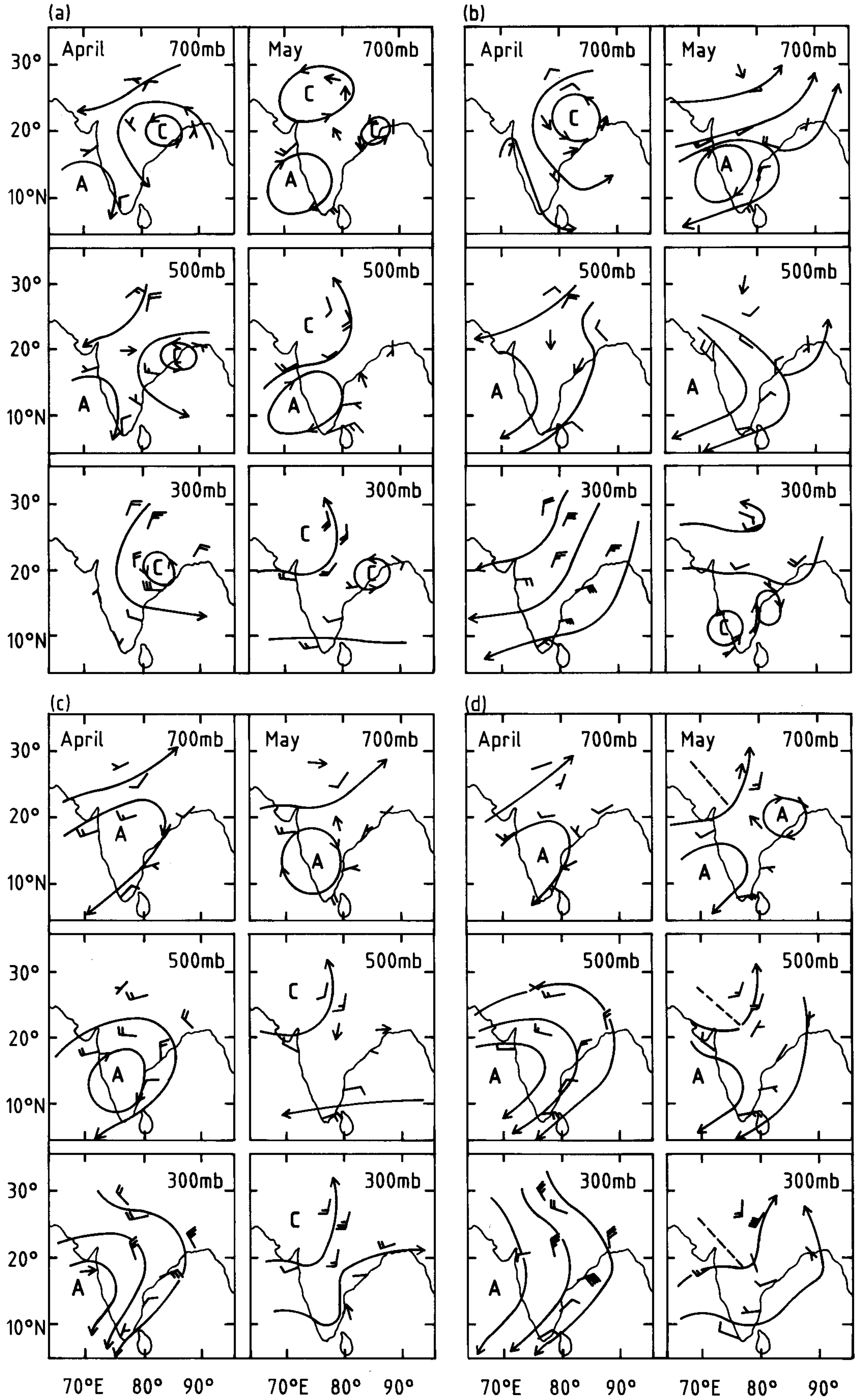

Figure 3. Anomaly circulations associated with the delayed monsoon at (a) Trivandrum, (b) Madras, (c) Bombay, (d) Visakhapatnam, (e) Nagpur, (f) Calcutta, (g) Lucknow and (h) New Delhi.

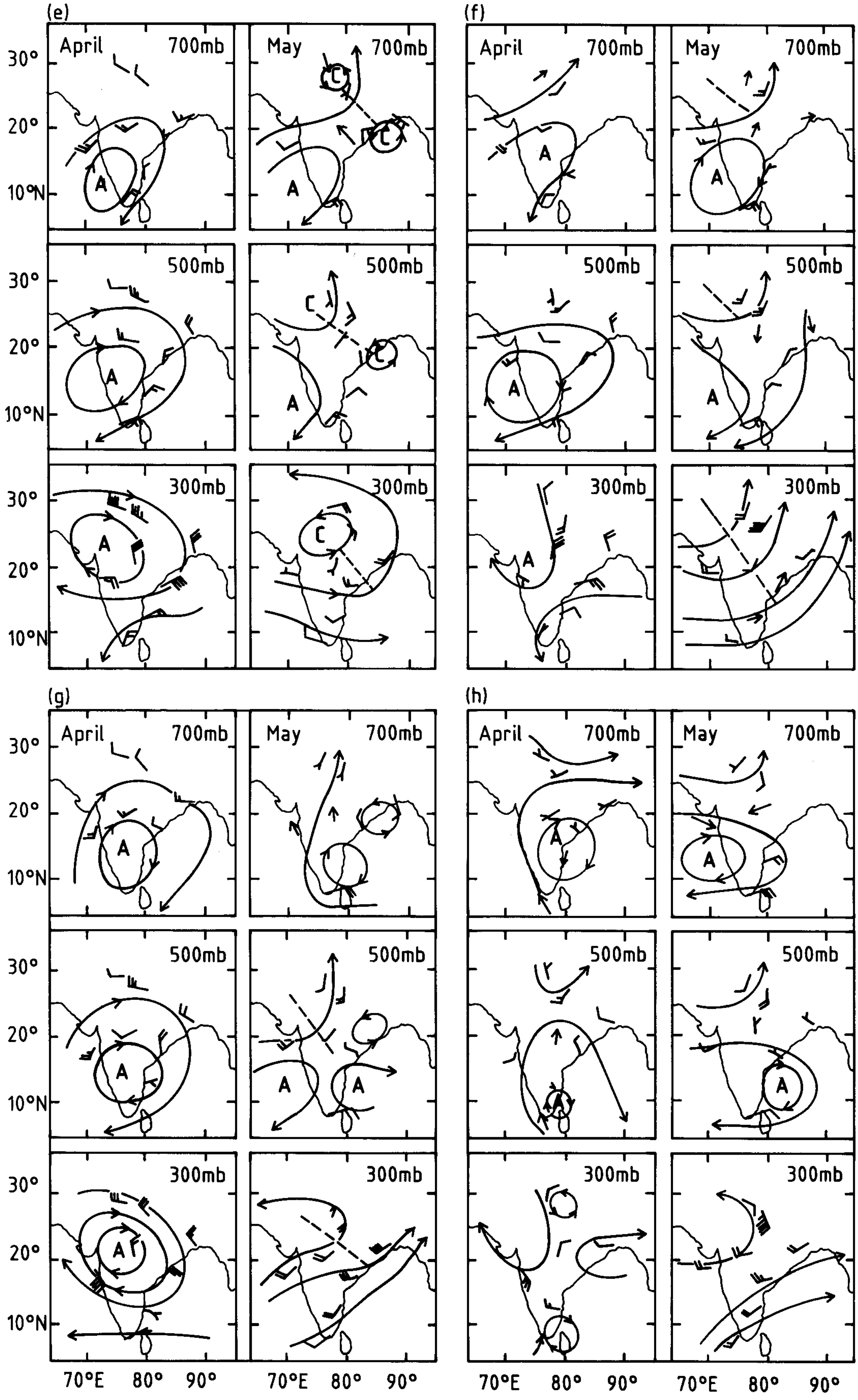

Figure 3. continued.

troposphere which extends into the upper troposphere but gradually shifts to the north with height. This indicates a meridional temperature gradient (increasing northwards) anomaly over western India. In May there is an anticyclonic circulation in the lower and middle troposphere over the west peninsula, and a significant cyclonic circulation over north-west India with a trough extending throughout the troposphere to the north Bay of Bengal.

Calcutta. The anomaly circulations in April (Fig. 3(f)) indicate anticyclonic circulation over west central peninsula in the lower and middle troposphere and a ridge in the upper troposphere over north-west India. In May the anticyclonic anomaly in the lower troposphere over west central peninsula persists and there is a trough over north-west India at all levels.

Lucknow. The anomaly circulations are shown in Fig. 3(g). In April there is a strong anticyclonic circulation, tilting northward with height, in the lower troposphere over the south of the peninsula. This anomaly feature is similar to that associated with the delayed monsoon at Nagpur. In May there is a trough over north-west India extending into central India in the middle and upper troposphere, and a ridge in the middle troposphere across the south of the peninsula. Also, there is a pronounced westerly anomaly in the upper troposphere across central India.

New Delhi. In April the correlations are small and the anomaly circulations show a weak anticyclonic circulation over the peninsula (Fig. 3(h)). In May the correlations are relatively high and significant. There is a ridge in the lower and middle troposphere across peninsular India and a strong cyclonic flow is present in the upper troposphere over north-west India.

3.3 Regression equations for forecasting the onset date of the monsoon

Wind parameters with good forecast values are selected as mentioned in section 2, and regression equations are developed to forecast the onset-date at each location. Two regression equations are obtained for each location, one involving the important wind component at the location itself and the other involving two significant wind parameters over the whole country. The first one is to enable the meteorologist at the location itself to prepare the forecast using data collected by them while the second one is to prepare a better forecast. At the locations where the onset generally takes place in May only one set of equations using April winds is developed, but at the other locations where the onset normally occurs after the first week of June, two sets of equations, one with April winds and the other with May winds, have been developed. The forecasting equations thus developed are given in the Appendix. Multiple correlations, standard deviations of the errors and the level of significance of the regressions are also noted.

All the regression equations are highly significant except some at Madras and Visakhapatnam. Those equations that are significant at the 1% level or more are indicated by asterisks. Some of the prognostic equations for the onset at Bombay, Calcutta and Lucknow have multiple correlations of 0.6 or more and these locations lie in the core-area of the Indian summer monsoon.

The standard deviation of the errors of estimates of these more significant equations is less than one week — this is still a large value. Nevertheless the equations would be useful in forecasting large deviations from the normal with good reliability in the absence of more accurate methods.

These equations have been used to produce onset forecasts for the year 1989 which are shown in Table I

Table I. Actual and forecast dates of onset of the monsoon in 1989

Location	Forecast dates				Actual dates
	April winds		May winds		
	Eq. 1	Eq. 2	Eq. 1	Eq. 2	
Trivandrum	13 May	8 May	—	—	20 May
Madras	5 June	5 June	—	—	5 June
Bombay	9 June	14 June	3 June	5 June	7 June
Visakhapatnam	9 June	12 June	—	10 June	8 June
Nagpur	13 June	11 June	—	12 June	12 June
Calcutta	9 June	8 June	9 June	10 June	12 June
Lucknow	4 July	3 July	—	25 June	23 June
New Delhi	—	—	—	5 July	13 July

along with the actual dates of onset. The dates forecast by the different equations are nearly the same at most of the locations except at Trivandrum and also in the case of one equation each at Bombay and Lucknow. Comparison of the forecast dates with the actual dates show large deviations at Trivandrum, Lucknow and New Delhi. However, the onset forecast at Lucknow with May winds gave a better result. Thus, the forecasts on the whole are reasonably good.

4. Conclusions

The onset dates are significantly correlated with winds in the pre-monsoon season at some locations. They reveal systematic anomaly circulations associated with delayed monsoon. These anomaly circulations related to the onset at different locations in general are:

(a) anticyclonic circulation over the west central peninsula in the lower troposphere,

(b) cyclonic circulation over north-west India in the upper troposphere, and

(c) westerlies over north India.

However, they differ in detail with the onset at different places.

The forecasts based on the present equations in 1989 are found to be reasonably good, particularly in the central parts of the country covering a large area.

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Appendix

In the following equations the zonal and meridional winds (m s^{-1}) are represented by *u* and *v*, respectively. The locations and levels of the winds are indicated by adding the appropriate location abbreviation and the pressure level as suffixes. The abbreviations used are BMB=Bombay, CAL=Calcutta, LKN=Lucknow, MDS=Madras, NDH=New Delhi, NGP=Nagpur, TRV=Trivandrum and VSK=Visakhapatnam. The multiple correlations (CC) of the equations, standard deviations of errors of estimates (SDE) and the level of significance (SIG) of the regressions are shown below each equation. Equations that are significant at the 1% level or more are indicated by asterisks.

Trivandrum (April winds)

(1) $\text{Onset} = 8.4 - 3.03v_{TRV700}$
CC = 0.42; SDE = 8.9 days; SIG = 5%

*(2) $\text{Onset} = -0.9 - 3.69v_{TRV700} + 1.54u_{VSK500}$
CC = 0.57; SDE = 8.1 days; SIG = 1%

Madras (April winds)

(1) $\text{Onset} = 34.3 - 0.56u_{MDS300}$
CC = 0.28; SDE = 8.3 days; not significant at 10% level

(2) $\text{Onset} = 34.0 - 0.39u_{MDS300} - 0.73v_{CAL300}$
CC = 0.4; SDE = 7.9 days; SIG = 5%

Bombay (April winds)

(1) $\text{Onset} = 29.5 + 1.78u_{BMB500}$
CC = 0.46; SDE = 7.3 days; SIG = 2%

*(2) $\text{Onset} = 23.2 + 1.81u_{BMB500} - 1.78u_{TRV500}$
CC = 0.6; SDE = 6.6days; SIG = 0.1%

Bombay (May winds)

*(3) $\text{Onset} = 35.6 + 3.09u_{BMB700}$
CC = 0.56; SDE = 6.7 days; SIG = 1%

*(4) $\text{Onset} = 35.4 + 2.15u_{BMB700} - 0.67u_{TRV700}$
CC = 0.58; SDE = 6.6 days; SIG = 1%

Visakhapatnam (April winds)

(1) $\text{Onset} = 37.5 - 1.16v_{VSK500}$
CC = 0.33; SDE = 6.7 days; SIG = 10%

(2) $\text{Onset} = 34.4 - 0.42v_{VSK500} - 1.25u_{TRV500}$
CC = 0.41; SDE = 6.4 days; SIG = 5%

Visakhapatnam (May winds)

*(3) $\text{Onset} = 41.5 - 1.07u_{TRV700} + 0.95v_{NDH500}$
CC = 0.54; SDE = 6.0 days; SIG = 1%

New Delhi (May winds)

*(1) Onset = $57.6 + 1.21u_{VSK300} - 1.25u_{TRV700}$
CC = 0.56; SDE = 7.5 days; SIG = 1%

Nagpur (April winds)

(1) Onset = $43.0 - 0.88v_{NGP300}$
CC = 0.45; SDE = 7.4 days; SIG = 2%

*(2) Onset = $35.2 + 2.33v_{BMB700} - 1.16v_{VSK500}$
CC = 0.62; SDE = 6.5 days; SIG = 0.1%

Nagpur (May winds)

(3) Onset = $54.0 - 1.02u_{TRV700} - 0.59u_{NDH300}$
CC = 0.43; SDE = 7.5 days; SIG = 5%

Calcutta (April winds)

(1) Onset = $34.2 - 1.55v_{CAL500}$
CC = 0.4; SDE = 6.4 days; SIG = 5%

*(2) Onset = $31.1 + 1.50v_{BMB700} - 1.27v_{CAL500}$
CC = 0.52; SDE = 6.0 days; SIG = 1%

Calcutta (May winds)

*(3) Onset = $36.1 - 1.48u_{TRV700}$
CC = 0.62; SDE = 5.5 days; SIG = 0.1%

*(4) Onset = $39.5 - 1.51u_{TRV700} + 0.92v_{NDH500}$
CC = 0.69; SDE = 5.1 days; SIG = 0.1%

Lucknow (April winds)

(1) Onset = $31.5 + 1.75u_{LKN500}$
CC = 0.48; SDE = 7.7 days; SIG = 5%

*(2) Onset = $25.9 + 2.0v_{BMB700} + 1.9u_{CAL500}$
CC = 0.64; SDE = 6.6 days; SIG = 0.1%

Lucknow (May winds)

*(3) Onset = $54.4 + 1.08u_{VSK300} + 0.60v_{LKN500}$
CC = 0.58; SDE = 7.5 days; SIG = 1%

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Modelling long-term rainfall patterns in north-east England

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Summary

Mean annual and monthly rainfalls from 133 gauges in north-east England have been used to study the variation of rainfall with height and location in this area.

1. Introduction

Rainfall is one of most important climatological elements. Despite a traditional reliance on rain-gauge data it must not be forgotten that they provide only point sample data from a geographically continuous population. The underlying character of that population can only be established by statistical inferential methods that model and generalize its behaviour, often in relation to other variables of which the three spatial dimensions of height and location (defined by Cartesian coordinates) are, arguably, the most important. This paper examines the utility of such models insofar as they are able to reproduce and, by inference, 'explain' the geography of rainfall. It takes as its point of departure the mean annual and monthly rainfalls from a sample of 133 gauges distributed over north-east England. Regression, and trend-surface methods are studied and their results used to identify underlying order and pattern in rainfall information.

Past efforts have been directed towards relating mean annual rainfall to altitude and to the spatial variables of latitude and longitude. Rodda (1962) used regression analysis of annual rainfall over 2 years to produce '...an objective method for assessment of areal rainfall amounts...', in this case based on 19 sites in mid-Wales. Unwin (1969) used trend-surface analysis to study systematic geographical variation in mean annual rainfall in the Snowdonia district. His study employed data from 47 stations and concluded with a multiple regression model based on altitude as well as the two spatial dimensions. Chuan and Lockwood's (1974) study covered much of Lancashire and Yorkshire and examined monthly, as well as annual, relationships between rainfall and altitude. The authors used data from 260 stations and studied also the effects of exposure and distance from the Pennine ridge.

The present paper takes a broadly similar approach and attempts to respond also to the prompting of Bleasdale and Chan (1972) who stressed the need for more detailed regional studies of rainfall patterns. It also complements the synoptic-based climatological studies such as those undertaken in the region by Jackson (1969) and elsewhere by, for example, Barry (1963).

The region comprises the 3300 km^2 of land which was administered by the Northumbrian Water Authority and which includes the counties of Durham, Northumberland, Tyne and Wear and parts of Cleveland and Cumbria. This region is not a mere administrative device but has strong claims to a geographical identity. Its boundaries are major hydrological divides of, by English standards, notable elevation; the Pennines to the west, the Cheviots to the north and the North Yorkshire Moors to the south (Fig. 1). Of equal geographic significance is the North Sea, forming the eastern limit of the region and comprising the coldest stretch of water along the British coast. The effect of the Pennines is especially noteworthy. In north-east England they achieve their greatest and most continuous heights and create a degree of climatic distinctiveness through the shelter they afford from the dominant westerlies. Manley (1935), for one, has been at pains to emphasize the integrity of the region's climate. The physiography of the region is helpfully uncomplicated, and consists of a Tertiary erosion surface tilting from west to east (Trotter 1929) and is disrupted only by the valleys of the region's three major rivers, the Tyne, Wear and Tees. The abrupt and irregular relief that characterizes so much of upland Britain is largely absent and so too, by inference, is the correspondingly complex geography of rainfall that, in these latitudes, is so often closely governed by height.

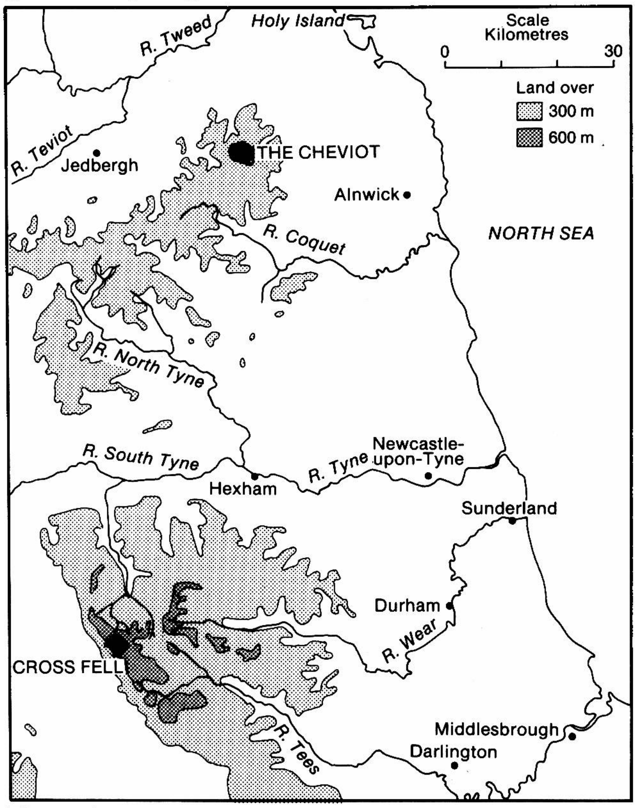

Figure 1. Relief map of north-east England showing principal rivers.

Because of the importance of altitude in the following analysis, the sample was stratified within 50 m altitudinal bands. Only at high level, and because of lack of stations, did this requirement have to be relaxed. The bias that might otherwise have resulted from the abundance of low-level stations was avoided and the skewness of the statistical distribution of station altitude was only +0.156.

2. Variation of rainfall with altitude

2.1 Annual rainfall

The geography of the region's rainfall is shown in Fig. 2. Visual comparison alone with Fig. 1 suggests a degree of correspondence between rainfall and altitude. Such an association has been appreciated for many years (Salter 1918). Table I summarizes the relationship between mean annual rainfall and altitude in the region and sets it against that for the adjacent Yorkshire area (Chuan and Lockwood 1974). The two show similar regression parameters and equally strong correlations between rainfall and altitude. Similar correlations were also found in Snowdonia (Unwin 1969) and in mid-Wales (Rodda 1962). Table I also gives the regression model for national data (Bleasdale and Chan 1972). In comparison with the latter, the north-east region has a lower intercept term and regression coefficient; expressed otherwise, both mean-sea-level rainfall and its rate of increase with altitude are significantly below the

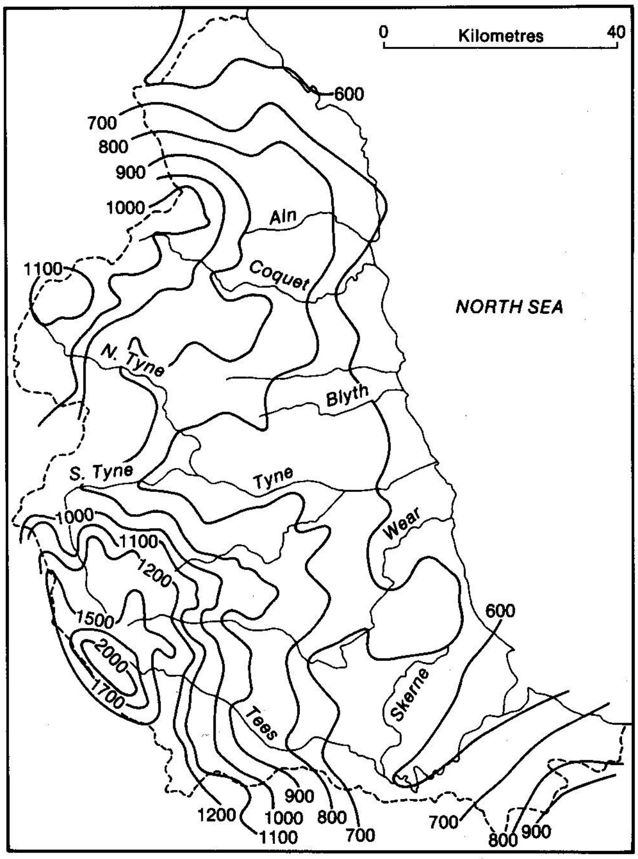

Figure 2. Isohyets of mean annual rainfall (mm) over north-east England.

national average and are an expression of the shelter from the rain-bearing westerlies.

2.2 Monthly rainfall

Variations between mean monthly rainfall–altitude associations have not received the wide attention given to annual data. Nevertheless the level of inter-monthly variation in average rainfall is in the order of 100 per cent and is matched by equally important variations in the relationships between rainfall and height. Regression and correlation coefficients are at a maximum in winter but a minimum in summer (Table II and Fig. 3). This result confirms Chuan and Lockwood's findings for the Yorkshire region and suggests it to be more than a local phenomenon. No published data exist to permit comparison with other regions of Britain. The nearest attempt at a corresponding exercise was that by Bleasdale and Chan (1972) who merely observed that winter (November to February) showed an 'intensification' of the rainfall–altitude correlation.

It should be emphasized that the similarity between monthly regression and correlation coefficient trends cannot be dismissed on statistical grounds and that the two parameters measure different aspects of the same bivariate population. This is important because it means that, for example, winter rainfall is not only more closely correlated with altitude but the rate at which it

Table I. Regression models of mean annual rainfall (Y) against elevation (X) for the United Kingdom and some of its regions. Coefficients of explanation (r^2) and correlation (r) are also given. Heights are in metres AMSL and rainfall in millimetres.

Region	Regression equation	$r^2(r)$
North-east England	$Y = 552.07 + 1.776X$	0.76 (0.87)
Yorkshire	$Y = 564.27 + 2.024X$	0.71 (0.84)
Mid-Wales*	$Y = 868.2 + 1.667X$	0.71 (0.84)
United Kingdom	$Y = 714.0 + 2.42X$	n/a

* Equation originally expressed in imperial units.

Table II. Correlation and regression analyses for mean monthly rainfall, Y(mm), and altitude, X(metres AMSL), in north-east England. In all cases the associations are significant at the 0.01 probability level.

Month	$r^2(r)$	Regression equation	Standard error of estimate of Y (mm)
January	0.79 (0.89)	$Y = 44.59{+}0.188X$	15.46
February	0.82 (0.90)	$Y = 35.77{+}0.163X$	12.18
March	0.79 (0.89)	$Y = 27.39{+}0.134X$	10.79
April	0.77 (0.88)	$Y = 30.38{+}0.127X$	10.98
May	0.68 (0.82)	$Y = 42.43{+}0.104X$	11.32
June	0.62 (0.79)	$Y = 41.73{+}0.086X$	10.25
July	0.47 (0.69)	$Y = 54.35{+}0.094X$	15.57
August	0.62 (0.79)	$Y = 67.19{+}0.145X$	17.71
September	0.73 (0.85)	$Y = 46.94{+}0.160X$	15.44
October	0.76 (0.87)	$Y = 39.48{+}0.178X$	15.79
November	0.77 (0.88)	$Y = 53.35{+}0.191X$	16.18
December	0.75 (0.86)	$Y = 36.97{+}0.205X$	18.76

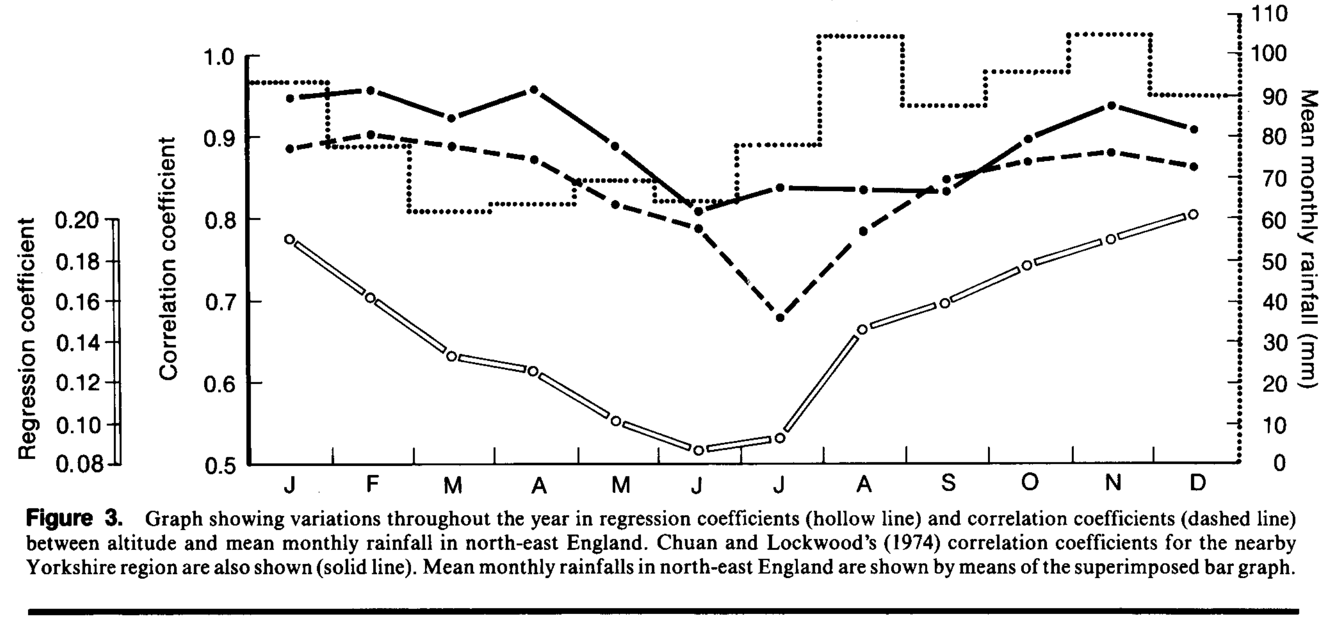

Figure 3. Graph showing variations throughout the year in regression coefficients (hollow line) and correlation coefficients (dashed line) between altitude and mean monthly rainfall in north-east England. Chuan and Lockwood's (1974) correlation coefficients for the nearby Yorkshire region are also shown (solid line). Mean monthly rainfalls in north-east England are shown by means of the superimposed bar graph.

increases with height is also more marked. On the other hand summer rainfall is less well correlated with altitude and simultaneously rises less quickly with elevation. Hence conclusions drawn from annual data may disguise important monthly and seasonal variations even in climates normally regarded as having a well distributed rainfall regime.

3. Spatial patterns of rainfall

Trend surface analysis allowed the geographical character of annual and monthly mean rainfall to be studied. The methodology is well described in King (1967) and need not be reviewed here other than to add that the use of a 'buffer' zone of points around but beyond the limit of study was impossible in the absence of rainfall data from the North Sea.

The spatial dimensions were defined in Ordnance Survey (OS) grid references to give 'eastings' (X co-ordinate) and 'northings' (Z coordinate). The linear trend surface model is given by

$$Y = \mathrm{a} + \mathrm{b}X + \mathrm{c}Z$$

where Y is mean rainfall and a, b, and c the constants.

Using the linear surface (Table III) the degree of variance explanation of rainfall is less than that obtained by a simple regression model based on altitude. On an annual basis the respective coefficients of explanation (r^2) are 0.76 and 0.65. However the quadratic and cubic models allow more flexibility in the fitted surface by using polynomial instead of linear expressions of the relationship between rainfall and location (Figs 4 to 6). The quadratic surface is described thus;

$$Y = \mathrm{a} + \mathrm{b}X + \mathrm{c}Z + \mathrm{d}X^2 + \mathrm{e}XZ + \mathrm{f}Z^2$$

and the cubic surface is given by;

$$Y = \mathrm{a} + \mathrm{b}X + \mathrm{c}Z + \mathrm{d}X^2 + \mathrm{e}XZ + \mathrm{f}Z^2 + \mathrm{g}X^3 + \\ + \mathrm{h}X^2Z + \mathrm{i}XZ^2 + \mathrm{j}Z^3.$$

With these expressions the degree of variance explanation is significantly improved from that obtained using the rainfall–altitude regression models (Table III). At the same time the pattern of greater winter, but decreased summer, degrees of variance explanation persist in the quadratic model. To paraphrase the findings, winter rainfall has a more clearly defined spatial pattern than does that of summer. Comparison with Unwin's (1969) work is difficult as the latter was carried out using 'equivalent (sea level) precipitation estimates' rather than the raw data. Given that Unwin had standardized his rainfall data prior to trend-surface analysis the results in Table III can only be seen as favourable. The quadratic and cubic surfaces in particular fall only little short of the efficiency of Unwin's models. This finding also suggests the difficulty of modelling the complex geography of local rainfall in an area such as Snowdonia a point which Unwin himself emphasized.

Table III. Trend surface analysis data for mean monthly and annual rainfall in north-east England. SEE is the standard error of estimate of rainfall (mm) and r^2 is the coefficient of explanation. In all cases the surfaces are significant at the 0.01 level.

Month	Linear		Quadratic		Cubic	
	r^2	SEE	r^2	SEE	r^2	SEE
January	0.66	19.45	0.80	15.08	0.82	13.24
February	0.67	16.37	0.78	13.47	0.82	11.44
March	0.67	13.59	0.80	10.61	0.84	8.98
April	0.67	13.10	0.81	10.06	0.83	8.70
May	0.63	12.14	0.75	10.06	0.79	8.62
June	0.56	11.28	0.72	9.13	0.77	7.69
July	0.55	14.43	0.76	10.73	0.80	8.92
August	0.61	18.13	0.75	14.69	0.78	12.75
September	0.69	16.48	0.81	12.30	0.85	10.73
October	0.65	18.96	0.82	13.72	0.85	11.72
November	0.61	21.30	0.76	16.81	0.80	14.36
December	0.67	21.40	0.84	14.97	0.86	13.02
Annual	0.65	188.4	0.80	145.3	0.82	126.8

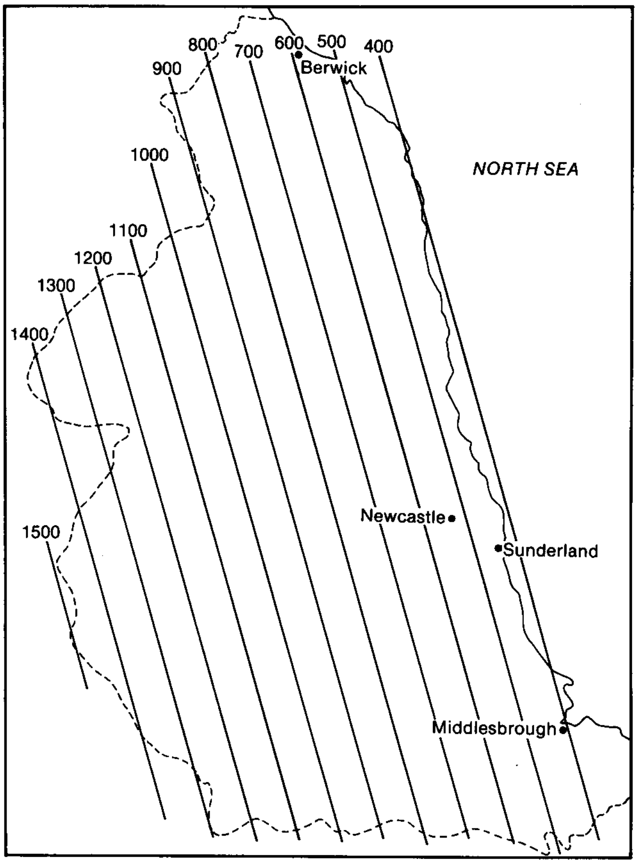

Figure 4. Linear trend surface for mean annual rainfall (mm) in north-east England.

4. Multiple regression models of rainfall

In the present study both northings (with $r = +0.22$) and eastings (with $r = -0.69$) are significantly correlated

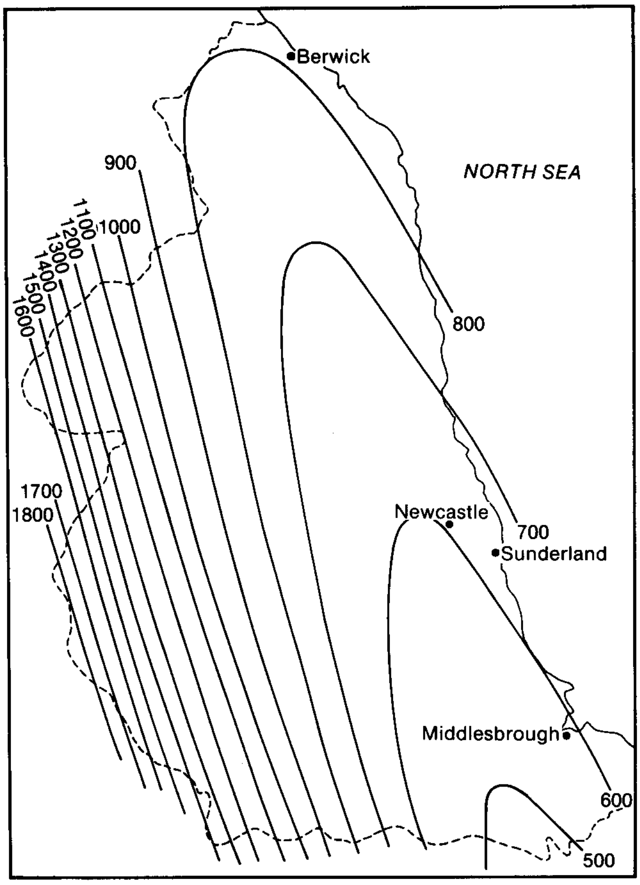

Figure 5. Quadratic trend surface of mean annual rainfall (mm) in north-east England.

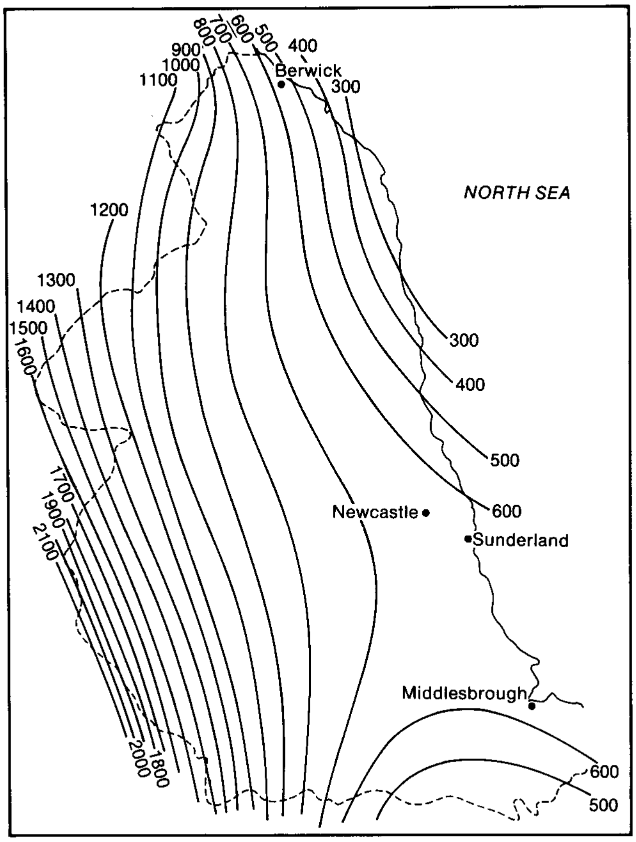

Figure 6. Cubic trend surface of mean annual rainfall (mm) in north-east England.

with altitude, i.e. altitude increases both northwards and westwards. In order to unravel the intercorrelations between the three variables the trend surface and regression approaches can be combined to employ altitude and the two spatial dimensions. In the linear case the method is one of straightforward multiple regression. In the higher-order polynomial quadratic and cubic treatments of the spatial coordinates the regression equation becomes a polynomial expression combined with a linear altitudinal component. The r^2 values of these models were, for all monthly and the annual data, above 0.83. While such a high order of variance explanation gives confidence in spatial interpolation between known points, they are less helpful when attempting to reveal the underlying trends from the inherently variable picture which nature presents to us. Attention is concentrated initially, therefore, on the simplest model

$$Y = \mathrm{a} + \mathrm{b}U + \mathrm{c}X + \mathrm{d}Z \qquad (1)$$

where Y is mean monthly or annual rainfall, U is the altitude, and a, b, c and d are constants or partial regression coefficients. The annual pattern of rainfall predicted from this model is shown in Fig. 7 and can be compared with the isohyets in Fig. 2. The pattern of positive and negative residuals shows a degree of spatial autocorrelation in which the model underestimates the rainfall in eastern districts generally and also on the highest ground of the Pennines in the far west of the region. No additional variable could be found to significantly reduce the degree of residual autocorrelation, indeed the very high coefficients of explanation associated with this model (Table IV) forcefully suggest that such a variable may not exist.

More usefully, the partial regression coefficients and beta weights gave a measure of the variables' independent contributions to rainfall; a contribution that again varies through the year (Table IV). It might be anticipated that the inclusion of altitude would render the spatial dimensions of marginal importance. Such, interestingly, was not the case. All the partial coefficients for altitude and eastings (longitude), and most for northings (latitude), are significant at the 0.05 level.

The partial regression coefficients for altitude are, as expected, smaller than their zero-order counterparts. The latter, however, measure the net regional effect of altitude on rainfall irrespective of other variables such as location, while the former measure the rate of rainfall change with height but with the locational element 'fixed' or 'controlled' but not removed. This change notwithstanding, the annual rhythm is again encountered with its now characteristic winter maximum and summer minimum.

The partial regression coefficients for eastings (which because of the geography of the high ground is all but

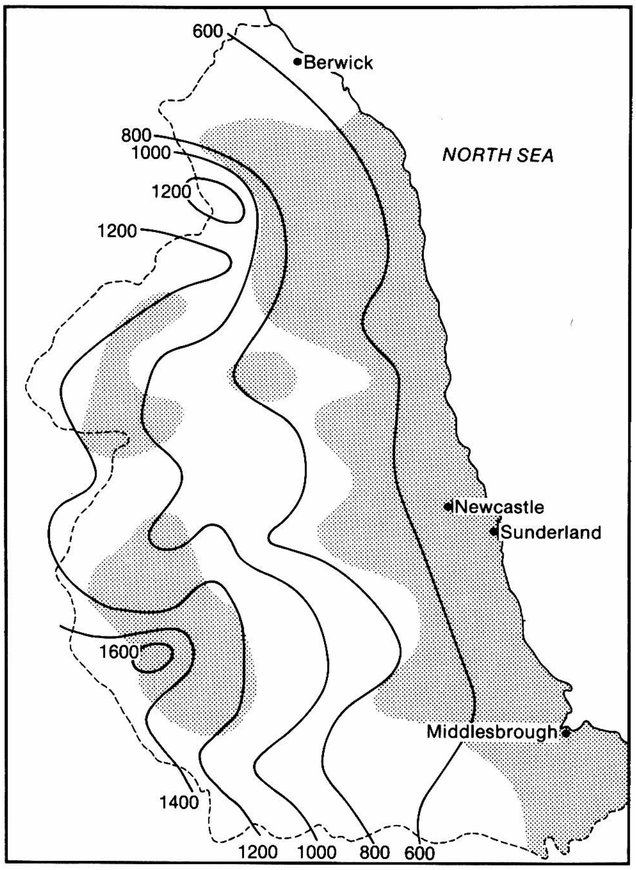

Figure 7. Map of modelled annual rainfall (mm) in north-east England based on a multiple regression model using height, eastings and northings as the independent variables. The stippled areas are those of positive residuals — clear areas are negative.

identical with distance from the Pennine watershed) are also significant. In this case it is altitude and longitude that are 'controlled' yet rainfall continues to decline eastwards along imaginary lines of constant elevation (and at rates indicated by the coefficients themselves). The effect is secondary to the altitudinal control, but is nonetheless important. Chuan and Lockwood (1974) also examined the effect of distance from the Pennine divide in Yorkshire, and found a corresponding relationship, but they did not examine its monthly character which here again shows variation with a more rapid eastwards decline in rainfall during the autumn and winter, but a less marked tendency during the spring and summer. In Unwin's (1969) Snowdonia study eastings, in contrast, played no significant role in the rainfall model.

No less intriguing is the pattern of rainfall change northwards. Again it is subordinate to altitude, but statistically significant in all but 3 months (May, June and September). The partial coefficients show the degree of rainfall change along imaginary longitudinal lines of fixed altitude. The magnitude of this effect again varies between the months. In summer it is positive, i.e. the rainfall tends to increase northwards, but at other times of the year it is negative, the rainfall tending to decrease northwards. The net effect is to obscure the importance of this dimension in the annual model where the partial coefficient is not significant. It can thus be demonstrated that the statistical and, by inference, climatological roles of the two spatial dimensions and altitude are independently exercised and to degrees that differ through the year.

Finally, turning back to the issue of modelling which seeks to reproduce reality and not necessarily simplify it, mention can be made of the most efficient of the models under study. These are the trend surface quadratic and cubic expressions containing an additional linear term for altitude. In respect of degrees of variance explanation these are unquestionably the most efficient, as Table IV demonstrates, and might well be the preferred tool of the hydrologist concerned more with extending rainfall records across areas of interest rather than with climatological investigation. They persist also in showing a less ordered scheme of rainfall in summer compared with that of winter, though the detailed rhythms are less clear. But such is the very character of these models that these underlying trends, so persuasively distilled in the simple models, are obscured in the variability that they permit. From this point of view climatologists might argue that the models are less useful having foresaken simplification for reproduction and inevitable complication.

5. The climatology of the region's rainfall

The above findings reaffirm the importance of altitude as a control on rainfall, but the degree of control was shown to vary. The summer minimum reflects the activity of convectionally driven rainfall which, by its very nature, is spatially random and less influenced by altitude than the winter cyclonic rainfall with its large-scale vertical motions, particularly within the humid warm sectors, over the Pennines. At the same time there is also a significant, and independent, locational element. Rainfall can be seen to decrease eastwards, even when the effect of altitude is 'controlled'. The average annual effect is a 490.66 mm decrease for every 100 km eastwards (100 km is the co-ordinate unit used in the models). The partial regression coefficient represents the rainfall change per unit distance, and here quantifies the rate of rainfall decrease eastwards; the loss of moisture through precipitation not being made up by evaporation or transpiration gains from the surface — it is, in fact, an acknowledgement of the 'rain shadow' effect isolated from the altitudinal influence. It appears, once again to be less well marked during the summer months. The influence varies between a 61 mm per 100 km decrease in December to only 23 mm per 100 km decrease in June. Northings or latitude, also exercise an independent influence. In August this reaches a peak of 18.68 mm per 100 km northwards increase, declining to a 29.4 mm per 100 km northwards decrease in December. Rainfall is known (Sawyer 1956) to decrease away from cyclonic centres. Given that depressions generally adopt eastward routes to the north of Britain in summer, but

Table IV. Partial regression coefficients used to predict mean annual and monthly rainfall (mm) in north-east England. The predictor variables are Ordnance Survey eastings and northings (expressed in units of 100 km) and station altitude (m). Multiple regression equation (1) was used to derive these monthly and annual models. Only those coefficients marked (*) are not significant at the 0.05 level. The three columns of r^2 values are for the (a) linear (equation 1), (b) spatial quadratic plus linear altitude, and (c) spatial cubic plus linear altitude models. Figures in parentheses beneath the partial regression coefficients are their respective beta weights (measures of their relative importance).

Month	Partial regression coefficients			r^2		
	Easting	Northing	Altitude	(a)	(b)	(c)
January	−48.53	−14.08	0.1398	0.82	0.91	0.92
	(−0.29)	(−0.12)	(0.66)			
February	−31.54	−19.18	0.1271	0.84	0.90	0.92
	(−0.22)	(−0.20)	(0.70)			
March	−30.12	−17.99	0.0999	0.83	0.91	0.92
	(−0.26)	(−0.23)	(0.66)			
April	−35.34	−15.05	0.0891	0.86	0.90	0.92
	(−0.31)	(−0.20)	(0.62)			
May	−32.43	5.55*	0.0777	0.76	0.87	0.91
	(−0.33)	(0.08)	(0.61)			
June	−23.32	4.33*	0.0676	0.70	0.84	0.86
	(−0.28)	(0.08)	(0.62)			
July	−37.35	14.21	0.0664	0.63	0.83	0.90
	(−0.35)	(0.20)	(0.49)			
August	−41.00	18.68	0.1163	0.75	0.87	0.91
	(−0.29)	(0.19)	(0.63)			
September	−61.44	−10.37*	0.1012	0.79	0.90	0.92
	(−0.42)	(−0.11)	(0.54)			
October	−49.78	−14.32	0.1283	0.79	0.92	0.93
	(−0.31)	(−0.13)	(0.63)			
November	−35.92	−11.42	0.1545	0.79	0.89	0.91
	(−0.21)	(−0.10)	(0.71)			
December	−61.25	−29.41	0.1389	0.79	0.92	0.93
	(−0.33)	(−0.24)	(0.59)			
Annual	−490.66	−87.67*	1.3066	0.79	0.90	0.92
	(−0.31)	(−0.08)	(0.64)			

shift southwards in winter, then the form of annual rhythm shown for the latitudinal effect would follow as a matter of course.

6. Conclusion

The results demonstrate clearly that, in this case at least, order in rainfall regimes and distributions can be both recognized and quantified to the advantage of hydrologists and climatologists. Spatial (trend-surface) models of quadratic and cubic form are preferred to regression models using spot heights, but the most efficient methods combine all three dimensions, height, latitude and longitude. It has also been shown that monthly models might be preferred to annual models when detailed reconstruction interpretations are sought.

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The spring of 1989 in the United Kingdom

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Summary

Spring was a season of some contrasts with a very cool April in most places, but a warm March and May; a very wet March over central and western areas of Scotland, and a very wet April in central England, then followed by a very dry May, exceptionally so in southern England, with record-breaking sunshine amounts.

1. The spring as a whole

Mean temperatures were below the seasonal normal in Northern Ireland and western parts of Scotland, but above normal everywhere else in the United Kingdom, ranging from 1.5 °C above normal in places in Kent and East Sussex to 0.4 °C below normal at Isle of Rhum, Western Isles.

Spring rainfall amounts were above normal over most of the United Kingdom although some eastern areas had well below average rainfall; however, the 153% of normal at Fort Augustus, Highland Region in the west contrasted somewhat with about 60% of normal around Newcastle upon Tyne in the east.

Spring sunshine amounts were about normal everywhere in the United Kingdom varying from around 90% in a few western areas to over 130% in the north Midlands.

Information about temperature, rainfall and sunshine during March–May 1989 is given in Fig. 1 and Table I.

2. The individual months

March. Mean monthly temperatures were generally above normal, ranging from near normal in the north and west of Scotland to more than 2.5 °C above normal just to the north of London. Much of East Anglia and south-east England had a very warm day on the 6th, one of the warmest early March days this century, with highest temperatures of 16 to 18 °C. On the 31st London Weather Centre measured 19.9 °C, the highest March temperature there for 21 years.

Monthly rainfall amounts were above normal in most parts of the United Kingdom with more than two and a half times the normal rainfall at Glasgow, Strathclyde Region. In contrast some eastern coastal areas of England and Scotland were rather dry and Newcastle upon Tyne had less than a third of its normal rainfall.

Sunshine amounts were generally above normal in Scotland, Northern Ireland and northern England but below normal in southern areas. The brightest area was eastern Scotland and north-east England with more than 120% of normal while south-west England and South Wales were generally rather dull with less than 80% of average sunshine.

The month started somewhat cool and windy but bright, then became unsettled and generally milder, with rain, persistent and heavy at times, and brighter showery interludes. Between the 20th and 23rd wintry conditions

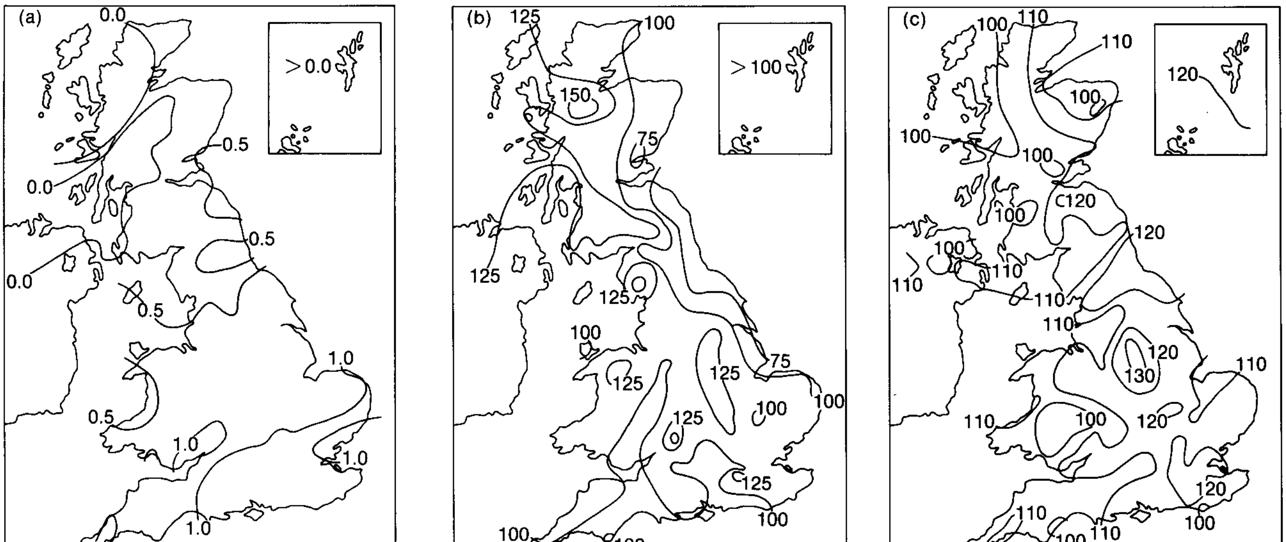


Figure 1. Values of (a) mean temperature difference (°C), (b) rainfall percentage and (c) sunshine percentage for spring, 1989 (March–May) relative to 1951–80 averages.

Table I. District values for the period March–May 1989, relative to 1951–80 averages

District	Mean temperature (°C)	Rain-days	Rainfall	Sunshine
	Difference from average		Percentage of average	
Northern Scotland	0.0	+2	108	104
Eastern Scotland	+0.3	0	98	113
Eastern and north-east England	+0.6	0	93	114
East Anglia	+0.9	0	106	110
Midland counties	+0.9	0	112	111
South-east and central southern England	+1.3	0	108	110
Western Scotland	−0.1	+2	111	105
North-west England and North Wales	+0.6	+1	120	109
South-west England and South Wales	+0.9	0	102	105
Northern Ireland	−0.1	+2	125	103
Scotland	+0.1	+1	110	107
England and Wales	+0.8	0	107	110

Highest maximum: 29.4 °C in south-east and central southern England in May.
Lowest minimum: −7.9 °C in western Scotland in March.

with snow and sleet and some hail pushed southwards from Scotland, temporarily reaching as far south as east Kent. After the 23rd the rest of the month became gradually more settled as the high pressure over the near Continent became established.

April. Mean monthly temperatures were below normal nearly everywhere in the United Kingdom, the main exception being Lerwick, Shetland with 0.2 °C above normal; at Exeter, Devon the mean temperature was nearly 2 °C below normal. At Oxford the mean monthly temperature was 1.3 °C below the normal; only 1903 and 1972 were lower in 109 years of records. Broom's Barn, Suffolk reported that the afternoon temperature of 5.2 °C on the 24th was the lowest maximum recorded in the last 10 days of April since the station opened in 1963. The temperature of 15.1 °C at Hampstead, Greater London on the 1st was the lowest April maximum there since 1972. Halesowen, West Midlands reported the lowest maximum since 1978 and the lowest night minimum since 1968.

Monthly rainfall totals were above normal in most places in England, Wales and Northern Ireland, but in many parts of Scotland amounts were below normal, as little as 40% at Kinlochewe, Highland Region. In contrast, Wyton, Cambridgeshire had more than 250% of normal. Wingerworth, Derbyshire reported the wettest April for 20 years. Hampstead, Greater London had the wettest April since 1983 and Coventry School (Bablake), Warwickshire the wettest since 1920.

Sunshine amounts were below average nearly everywhere, the exceptions being parts of central southern England, south-west England and southern and western Wales where sunshine was slightly above average, ranging from about 70% of normal in south-east England to 109% of normal at Plymouth, Devon and Aberporth, Dyfed.

April was generally cool and unsettled, with rain or showers at times. Snow occurred in many places in the first week, especially on the 5th with some reports of blizzard conditions over higher ground. On the 7th a golfer was struck by lightning at Southampton and badly burned. A mean wind of 49 kn was recorded at Milford Haven, Dyfed on the 11th, with a new record gust for April of 84 kn, while Aberporth recorded a gust of 78 kn, the highest April gust there for over 50 years. The strong winds brought chaos to the roads, and battered ships in the Irish Sea, blew down trees and caused structural damage to buildings throughout Wales. Thousands of homes in Devon and Cornwall and south-west and central Wales were without power after falling trees brought down overhead power cables. On the 13th Halstead, Essex had a violent thunderstorm with heavy rain and hail between 1830 and 2015 and local flooding; hail lay to a depth of 5 cm for a while.

May. Monthly mean temperatures were above normal in all areas, ranging from just above normal in parts of western Scotland to more than 3 °C above normal in the London area. The overall mean temperature of 14.4 °C and the maximum of 19.7 °C at Hampstead, Greater London were the highest for May since records began there in 1909; at Oxford the mean temperature was the highest since May 1952. On the 21st the temperature at Kinlochewe, Highland Region reached 27.4 °C and at Cape Wrath, Highland Region a maximum of 24.4 °C was recorded, the highest May value in a record that goes back to 1940. On the 24th the temperature at Wyton reached 28.4 °C, the hottest May day at the station since records began in 1954. The mean temperature at Newtown Linford, Leicestershire was the highest for May at the station for 25 years. It was the warmest May recorded at North Wyke, Devon since the record began in 1960.

Rainfall was well below average except in some north-eastern parts of Scotland where it was nearer normal, reaching 104% at Lerwick, Shetland. Parts of eastern and southern England were particularly dry although local thundery outbreaks produced variable amounts of rain; for example Farnborough, Hampshire received 117% of its May average, while London Weather Centre, 50 km away had only 2%. Central London had its driest May for about 300 years and over England and Wales as a whole it was the driest May since 1896. Many places in the south and east had less than 10 mm of rain and a number of places in Kent including Manston and Ulcombe had less than 1 mm and Faversham and Herne Bay were among several places reporting nil rainfall. Ryhope, Co. Durham and Letheringham, Suffolk also reported nil rainfall. Worthing, East Sussex and Durham had the driest May since records started there in 1902 and 1886, respectively. At Oxford, about 95% of the month's rain fell during a thunderstorm on the 24th. On the same day 63 mm fell at Mickleham, Surrey and 60 mm at South Farnborough, Hampshire.

Monthly sunshine amounts were above normal over the whole of United Kingdom, reaching 163% of the average in central London, but only just above normal, 102%, at Benbecula, Western Isles. Some places measured record amounts of sunshine, with most places south of a line from south Devon to north Norfolk measuring in excess of 300 hours; the last time such a large area of the United Kingdom experienced sunshine totals of over 300 hours in May was probably 1909. Oxford reported the highest May sunshine amount (301 hours) in 110 years of record.

The month was warm, dry and sunny generally. However, thunderstorms developed over East Anglia on the 11th and 12th and north-west England and North Wales on the 19th when a flash flood at Halifax, West Yorkshire caused considerable damage. On the 20th and 21st there were thundery showers in the south-west; on the 22nd thunderstorms developed over southern England and moved north-westwards. On the 23rd and 24th widespread thunderstorms brought floods to central and southern England, the Midlands and northern areas. On the 24th Easthampstead, Berkshire recorded hailstones up to 23 mm in diameter. A marked dust devil was reported at Hurst Green near Oxted, Surrey during the afternoon of the 9th. It lifted garden furniture and raised a child's metal slide 4 m into the air and carried it nearly 12 m.

Review

The human impact of climate uncertainty, by W.J. Maunder. 154 mm × 233 mm, pp. xxv+170, *illus.* London, New York, Routledge, 1989. Price £10.95 (paperback), £25.00 (hardback).

The author introduced the field of economic climatology to the scientific community in *The value of weather* (1970) and to the business community in *The uncertainty business* (1986). In the current volume he presents a broad view to the non-specialist of the role of weather and climate information in economic, social and political decision making.

The author presents the simple, infancy state of this topic as it exists and a proposed future in which the variable nature of the atmosphere must be acknowledged as an integral part of resource management. As an important component of the Earth's resources the atmosphere must be monitored carefully, its interaction with other components investigated and the value of weather/climate information assessed. The need for this work and progress so far forms the main theme of this book. There are 11 chapters, many examples mostly from New Zealand or the USA and extensive, up-to-date bibliographies.

The first two chapters examine the conflicting views of those who see economic climatology as 'non scientific', hence inherently undesirable and of little use, and those who regard it as beneficial and essential in a world of increasing population, pressure on resources and sensitivity to weather variations. An historical review of the development of climatology from static description to an evolving and interactive component of decision making is discussed.

Chapters III to V form a crucial foundation for subsequent chapters. Firstly the components of the atmospheric resource and the concept of limitation or adaptive responses to specific changes in this resource are outlined. The international institutional framework for atmospheric matters is considered. Current climate-change issues such as greenhouse warming are reviewed briefly and used to illustrate political implications of climate change. These are then set within the decision-making framework. Dissemination of climate/weather information from the scientist to the decision maker is critically evaluated and the value of this information as opposed to weather sensitivity itself is stressed. Facilities for monitoring and forecasting weather/climate are introduced and a severe criticism raised that the research in this area is not yet being matched adequately by that in application and sensitivity analysis.

A chapter on climate impacts and sensitivities is very general although it has useful forward references to examples in later chapters. It is stressed that the meteorologist must express sensitivites in a usable form.

Probably one of the most interesting and important topics is that of commodity-weighting weather data with respect to its economic influence for decision making. Weather anomalies are assessed in terms of the spatial distribution of the anomaly relative to that of commodity production and the contribution of the commodity to the national economy. This is illustrated well with examples from New Zealand and the USA.

Chapters VIII and IX illustrate the role of weather information in management and planning in agriculture, electricity production, manufacturing, retail trade, construction and transport. Each section is in itself a fairly cursory overview of the specific topic but are illustrated by many examples from around the world.

This theme is built up on in chapter X. Here the author suggests the current and future role of weather information in production forecasting and assessment by use of commodity weighted weather/climate information in explanatory or empirical models.

The book is concluded in chapter XI (which is confusingly numbered IX) with a look to the future of this topic. It begins with an imaginative futuristic agenda for a day in the life of a weather administrator in 1994. It is envisaged that, within a decade, meteorologists must be making significant contributions to economic and political decisions.

The whole book is packed with exciting examples. A thorough, although sometimes repetitive, case is presented for increased effort to treat the atmosphere as a valuable resource to incorporate weather/climate information in political and economic decision-making. It is an interesting and challenging introductory text for non-specialists in this field, but any specialist in the many contributory disciplines may be disappointed by the depth of discussion in their particular field.

M.F. Mylne

Satellite photographs — 24 January 1990 at 1515 UTC and 25 January 1990 at 0330 and 1325 UTC

The photographs in Figs 1 to 3 were taken at approximately 12-hour intervals during cyclogenesis of the storm that caused extensive wind damage and loss of life over southern Britain on 25 January 1990. The locations of the superimposed synoptic features are based on evidence derived from imagery and conventional surface data (interpolated where necessary using data from main synoptic hours).

The cloud pattern on the visible image (Fig. 1) suggests two distinct frontal zones — 'F' associated with the main jet stream, and 'P' being a secondary frontal zone forming in the cold air mass. The overall cloud area, encompassing cloud associated with both fronts, constitutes a 'cloud head' characteristic of impending explosive cyclogenesis and generation of hurricane force winds*.

During subsequent cyclogenesis (Figs 2 and 3) the wave on front 'F' gradually sharpens, but the part of the front 'P' behind the low accelerates around the right flank of the low so as to leave a core of warm air near its centre. This also occurred during development of the October storm of 1987† and in each of the intense depressions that crossed southern and central Britain during the stormy period of January and February 1990. The most active front (in terms of thermal contrast) was always the 'bent-back' warm front (not an occlusion) around the left flank of the low, and the strongest winds (stippled area in Fig. 4) always occurred at and behind the secondary cold front 'P' in an area bounded by the bent-back front.

The frontal analyses shown here are consistent with thermal fields derived from the UK fine-mesh model. The warm core and bent-back front are clearly evident in the 850 mb wet-bulb potential temperature field shown in Fig. 4.

G.A. Monk

* Bottger, H., Eckhardt, M. and Katergiannakis, U.; Forecasting extratropical storms with hurricane intensity using satellite information. *J Appl Meteorol*, **14**, 1975, 1259–1265.

† Monk, G.A. and Bader, M.J.; Satellite images showing the development of the storm of 15–16 October 1987. *Weather*, **43**, 1988, 130–135.

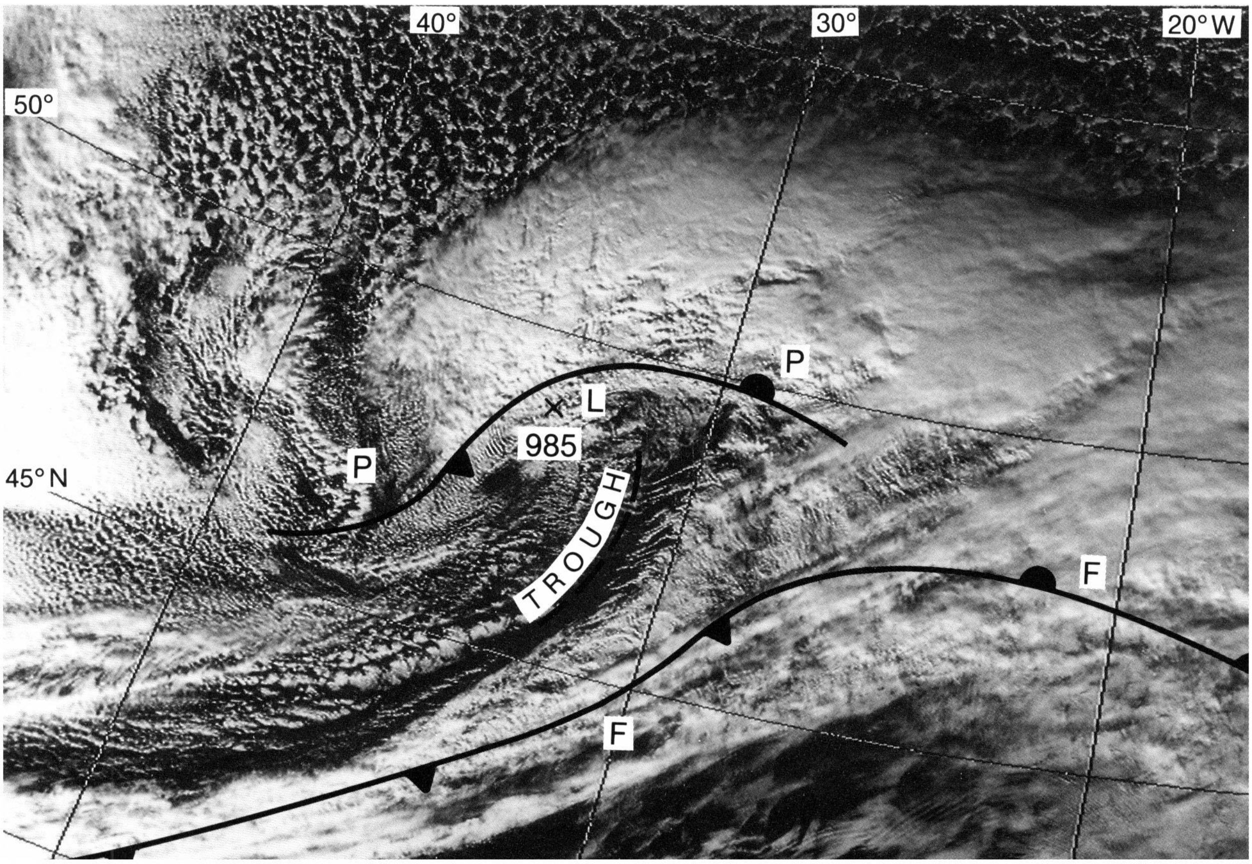


Figure 1. NOAA-11 visible image at 1515 UTC on 24 January 1990 with fronts and surface low superimposed.

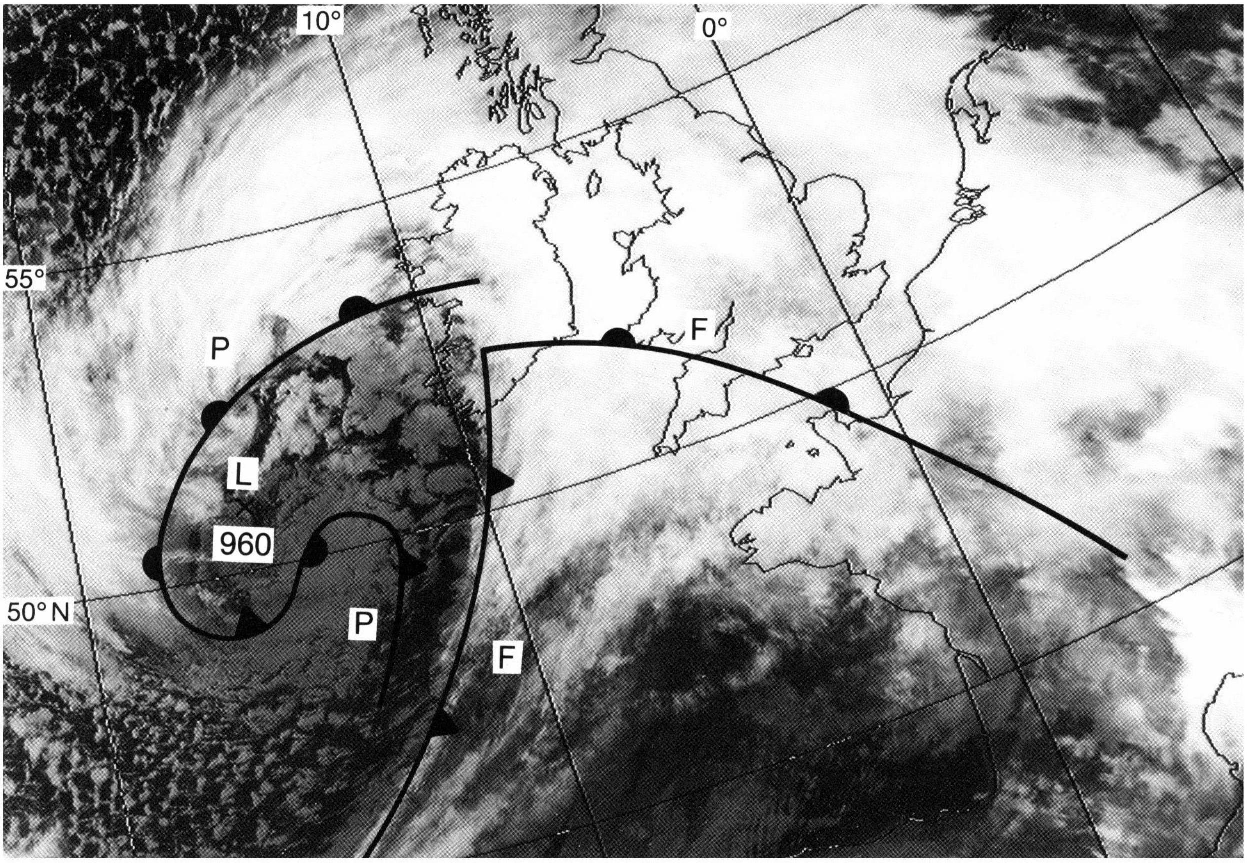
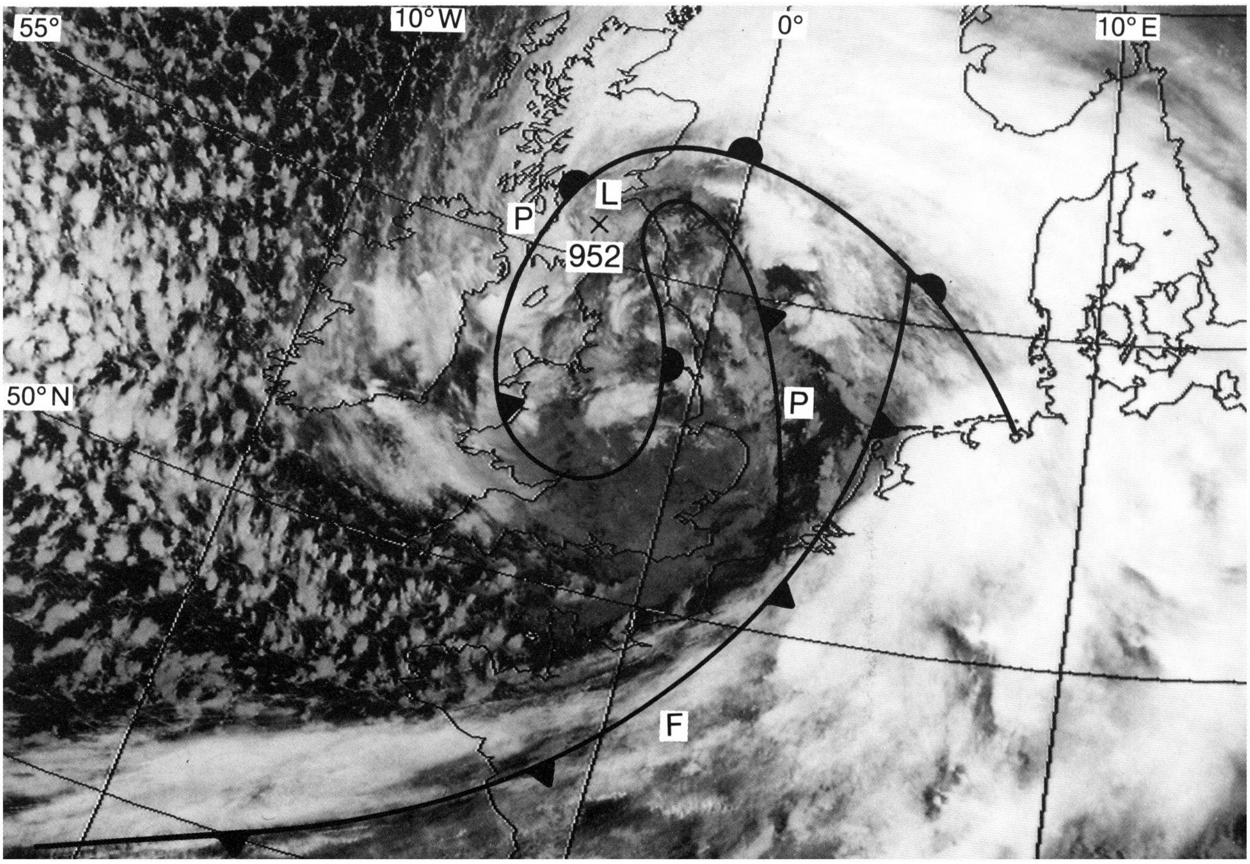


Figure 2. NOAA-11 infra-red image at 0330 UTC on 25 January 1990 with fronts and surface low superimposed.



Photographs by courtesy of University of Dundee

Figure 3. NOAA-11 infra-red image at 1325 UTC on 25 January 1990 with fronts superimposed.

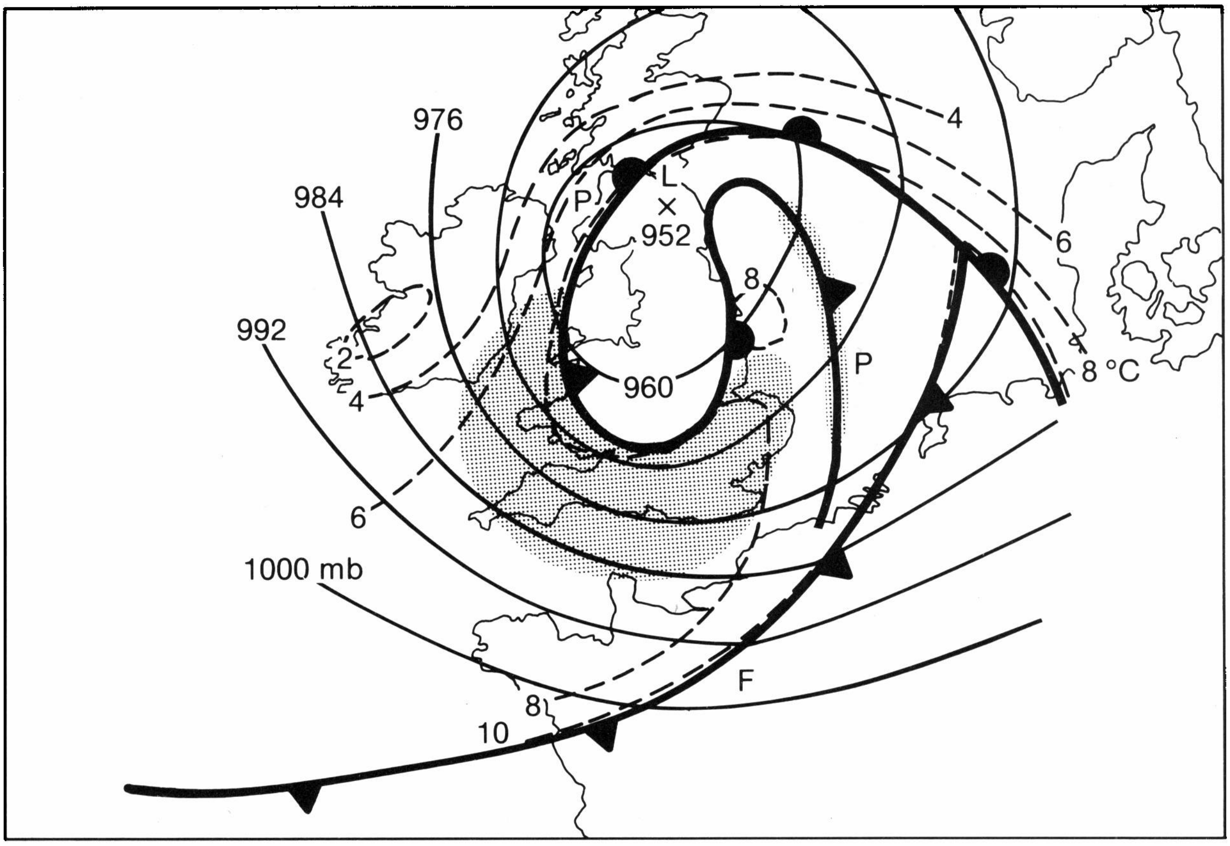


Figure 4. Surface isobars, isopleths of 850 mb wet-bulb potential temperature (°C) (dashed lines — from the 1200 UTC analysis of the fine-mesh model) and the region of strongest winds (stippled area) at 1300 UTC.

GUIDE TO AUTHORS

Content

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Preparation and submission of articles

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (Compucorp or IBM-compatible) can be labour-saving, but only a print-out should be submitted in the first instance.

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