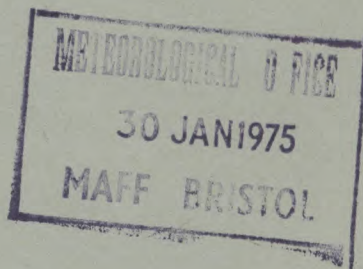


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THE WARMING AND MOISTENING OF COLD AIR MASSES BY THE SEA

By K. GRANT

Summary. An empirical formula for the change in temperature of cold air crossing a warmer sea is based on a hypothesis adopted for the sea-to-air heat-transfer coefficient. The formula is tested by using routine synoptic observations made in cold airstreams reaching the British Isles. A formula, due to J. A. Businger, for the increase in humidity mixing ratio is also tested.

Practical details are given of the use of the formulae.

Introduction. Blackall¹ has recently produced the following empirical formula for the increase in temperature of cold air as it crosses a warmer sea:

$$T = T_0 + (1 - \exp(-12t/d)) (T_s - T_0). \quad \dots (1)$$

(All symbols used are defined in Appendix I.)

This paper presents the results of an attempt to find an alternative empirical formula for T which would give smaller root-mean-square (r.m.s.) errors than the above equation, and also the results of a test of Businger's² theoretical formula for humidity change.

The prognostic equations for temperature. The working hypothesis was adopted that the heat-transfer coefficient C_H could be represented by

$$C_H = \beta \left(\frac{T_s - T}{\bar{T}} \right)^\alpha,$$

that is, that C_H is proportional to a constant unknown power of the sea-air temperature difference divided by the mean air temperature. By using an argument similar to that used on page 66 of Blackall's paper,¹ but starting from the basic equation $H = c_p \rho C_H V (T_s - T)$, this hypothesis leads to the prognostic equations

$$T = T_0 + [1 - \exp(-\rho g \beta s/d)] (T_s - T_0) \quad \dots (2)$$

if $\alpha = 0$, and

$$T = T_0 + \left[1 - \left(1 + \frac{\alpha \beta \rho g}{\bar{T}^\alpha} \cdot \frac{s}{d} \cdot (T_s - T_0)^\alpha \right)^{-1/\alpha} \right] (T_s - T_0) \quad \dots (3)$$

if $\alpha \neq 0$.

Determination of α and β from Blackall's synoptic data. Blackall's data were examined, and, by making use of 23 of his sets of initial conditions covering 15 different days, revised estimates of terminal temperatures and dew-points were made, with a view to obtaining the temperatures right on the coast, and the dew-points a little way inland. It was hoped that this would reduce the effects of the diurnal modification of temperature over land and the possibly strong vertical gradient of humidity at low levels over the sea and coastal areas.

For various values of α the minimum r.m.s. error and the associated optimum value of β were calculated, a range of β being used for each value of α . From these the optimum value of α and the corresponding value of β for overall minimum r.m.s. error in the forecast final temperature T were found. The sea-level air density ρ was obtained by assuming a constant sea-level pressure of 1013 mb in all cases, with \bar{T} equal to $(T + T_0)/2$. The gas constant R was taken as $287 \text{ J kg}^{-1} \text{ K}^{-1}$ (the value for dry air) and g as 9.81 m s^{-2} . The results are shown in Figure 1.

An overall minimum r.m.s. error of 0.6 degC is seen to occur at $\alpha \approx 2$. On the evidence of this analysis it was decided to adopt a value of exactly 2 for α , and the corresponding value of 3.8 for β (note that the optimum value of β changes substantially for the various values of α which were tested).

The effect of using virtual temperature was similarly explored. A minimum r.m.s. error of 0.57 degC at $\alpha = 2.2$ was found (with $\beta = 3.2$ for $\alpha = 2$). It was concluded that no significant benefit was to be gained by using virtual rather than dry-bulb temperatures, at least in these circumstances when air temperatures are around or below 5°C .

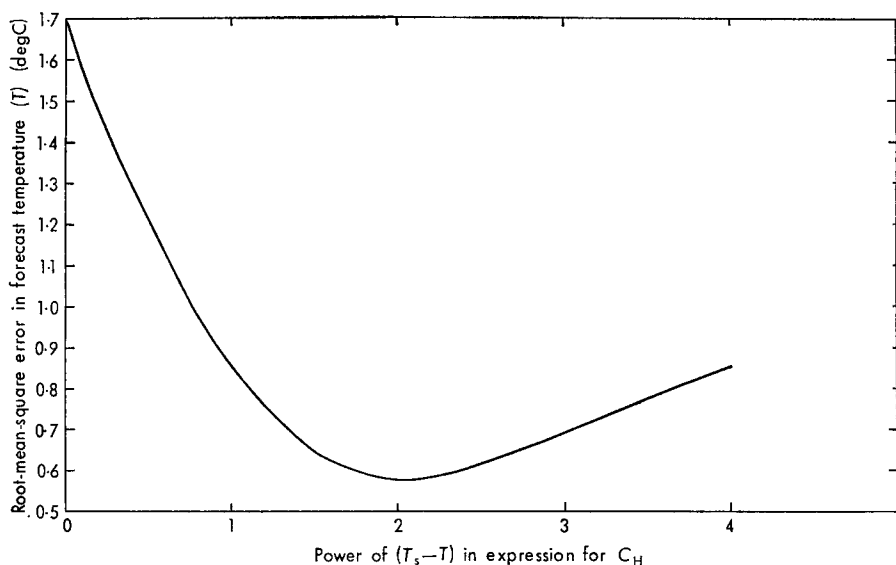


FIGURE 1—EFFECT ON ACCURACY OF FORECAST TEMPERATURE OF VARYING α IN $C_H = \beta (T_s - T_0)\alpha/T\alpha$

The β which gives minimum root-mean-square error in forecast temperature is used for each value of α .

The explicit formula for temperature. When the values of α and β determined above are substituted, the air density ρ is replaced by $p_s/R\bar{T}$, the fetch s is expressed in terms of units of degrees of latitude (1 degree of latitude \approx 60 nautical miles \approx 111 km), and the depth d in millibars, equation (3) becomes

$$T = T_0 + \left[1 - \left(1 + \frac{N(T_s - T_0)^2 s}{d} \right)^{-\frac{1}{2}} \right] (T_s - T_0), \quad \dots (4)$$

where $N = 2.92 \times 10^4 p_s / \bar{T}^3$ (p_s being expressed in millibars and \bar{T} in kelvins). N varies slowly with temperature and pressure as shown in Table I.

TABLE I—VARIATION OF N WITH TEMPERATURE AND PRESSURE

	p_s (mb)			
	980	1000	1020	1040
\bar{T} °C	N			
+10	1.26	1.29	1.31	1.34
+8	1.29	1.31	1.34	1.37
+6	1.32	1.34	1.37	1.40
+4	1.34	1.37	1.40	1.43
+2	1.37	1.40	1.43	1.46
0	1.40	1.43	1.46	1.49
-2	1.43	1.46	1.49	1.52
-4	1.47	1.50	1.53	1.56
-6	1.50	1.53	1.56	1.59
-8	1.53	1.57	1.60	1.63
-10	1.57	1.60	1.63	1.67

Businger's theory of humidity-mixing-ratio change. On the assumption that $C_E = C_H$ and that r is constant with height through the convection layer, it might be expected that the formula for the evaporative flux E would be analogous to that for H . Businger, in Section 5.10 of Fleagle and Businger,² showed that this is not so, the difference being that only the temperature, not the mixing ratio, determines the depth of dry convection.

Businger's formula is

$$r = r_0 + Z(r_s - r_0), \quad \dots (5)$$

where Z is a factor depending on the temperature increment through the relations

$$Z = 1 + \frac{1 - Y}{Y} \ln(1 - Y)$$

$$\text{and } Y = (T - T_0)/(T_s - T_0).$$

An interesting point here is that when Y is in the range 0.4 to 0.9 (as in practice it quite often is), Z is very nearly equal to $Y - 0.2$. This implies that if Frost's³ temperature formula $T = T_0 + 0.6(T_s - T_0)$ (where T_0 here is the unmodified initial surface air temperature) is accepted as being sufficiently accurate, then the appropriate constant in his mixing-ratio formula is not 0.6 but 0.4.

Test of Businger's formula based on the use of dew-point data.

Businger's formula was checked by using the dew-point and temperature data for the 23 occasions mentioned above. The mean error in dew-point was -0.36 degC and the standard deviation of the errors was 0.95 degC. These values compare with Blackall's values (relative to his own terminal values) of -0.6 degC and 2.1 degC respectively, and show an improvement in r.m.s. error which is significant at the 0.1 per cent level.

During this work it was noticed that dew-points at stations actually on the coast often tended to be higher than those reported inland by about $1-2$ degC. Most of this change appeared to arise close to the coast.

An independent check of performance. Tests of the performance for the British Isles of equations (4) and (5), as well as that of other methods, were carried out by Hedge⁴ who used independent data and trajectories determined from forecast charts as well as from actual charts. The results for actual charts are shown in Table II.

Table II shows that, in the relatively shower-free easterlies (average sea fetch 180 nautical miles), the variances of the errors in the present method are significantly smaller than those of Frost at the 5 per cent level, but the reduction of Blackall's variances by about one-third is not significant for a sample of only 30 trials. (If this apparent reduction in variance is true, however, the odds against obtaining a result which is significant at the 5 per cent level from 30 trials are 3 to 1.)

In the more showery northerlies (average sea fetch 230 nautical miles), there is little to choose between Blackall's method and the present method, though Blackall forecasts the coastal dew-points better. Frost's method shows large positive mean errors but with surprisingly small standard deviations. In these conditions none of the methods tested really achieved a satisfactory performance.

It is interesting that in Table II the mean errors in dew-point found by Grant's method are -2.0 degC for easterlies and -1.6 degC for northerlies. It would appear that Businger's formula tends to forecast inland rather than coastal dew-points.

Practical procedure

(a) *Forecast technique.* Use the technique to forecast surface air temperatures and dew-points at sea or at coastal stations (also inland when vertical heat- and water-vapour fluxes are small) in air with near-surface temperatures lower than the underlying sea surface temperature, when an upwind radiosonde ascent is available.

(b) *Sea fetch (s).* Decide on the trajectory and the representative speed V of the cold air. Write down the expected time of arrival of the air at your station (using V) and the length s of fetch over the sea in units of 1 nautical mile or 60 nautical miles (≈ 1 degree of latitude).

(c) *Sea temperature (T_s) and saturation mixing ratio (r_s).* Write down the mean value of these as accurately as possible.

TABLE II—ERRORS OF THREE METHODS OF FORECASTING TEMPERATURE AND DEW-POINT IN COLD-AIR ADVECTION OVER THE SEA
FROM 'ACTUAL' CHARTS (AFTER HEDGE⁴)

(a) Easterlies (30 trials)								(b) Northerlies (21 trials)							
TEMPERATURE								TEMPERATURE							
Method		Frost		Blackall		Grant		Frost		Blackall		Grant			
Mean error (degC)		0.7 ± 0.3*		0.4 ± 0.2		-0.2 ± 0.2		3.0 ± 0.4		1.5 ± 0.5		1.4 ± 0.4			
'Student's' <i>t</i>		2.48		2.05		0.89		7.87		2.98		3.30			
<i>P</i>		0.01		0.05		> 0.10		0.01		0.01		0.01			
Root-mean-square error (degC)		1.62		1.27		0.98		3.43		2.74		2.45			
Standard deviation of error (degC)		1.5 ± 0.2		1.2 ± 0.1		1.0 ± 0.1		1.7 ± 0.3		2.3 ± 0.4		2.0 ± 0.3			
Methods		Frost/Blackall		Frost/Grant		Blackall/Grant		Frost/Blackall		Frost/Grant		Blackall/Grant			
<i>F</i>		1.54		2.30		1.49		1.84		1.38		1.30			
<i>P</i>		> 0.10		0.02		> 0.10		0.10		> 0.10		> 0.10			
DEW-POINT								DEW-POINT							
Method		Frost		Blackall		Grant		Frost		Blackall		Grant			
Mean error (degC)		3.8 ± 0.4		1.0 ± 0.3		-2.0 ± 0.3		5.2 ± 0.4		0.3 ± 0.6		-1.6 ± 0.6			
Root-mean-square error (degC)		4.32		2.09		2.53		5.55		2.46		3.08			
Standard deviation of error (degC)		2.2 ± 0.3		1.9 ± 0.2		1.6 ± 0.2		1.9 ± 0.3		2.5 ± 0.4		2.7 ± 0.4			
<i>F</i>		1.32		1.89		1.43		1.73		2.00		1.16			
<i>P</i>		> 0.10		0.05		> 0.10		> 0.10		0.07		> 0.10			

* The numbers after the \pm signs are the standard errors of the numbers in front of them, with rounding to one place of decimals.

Notes:

- (a) 'Student's' t here is the difference between the mean unrounded error and zero, divided by the standard error.
- (b) F is the ratio of the larger of the squares of the standard deviation of error to the smaller, for each pair of methods.
- (c) P is the significance level reached by the value of t or F .

rule does not apply, but with experience r_0 should be determinable to within 0.1 g kg^{-1} and is given by the modified mixing ratio below the LCL (Figure 2).

(g) *Final temperature (T)*. Use the nomogram (Figure 3) to obtain the rise of surface air temperature ΔT and thence the final downwind temperature $T = T_0 + \Delta T$. Figure 3 is constructed for N equal to 1.40.

(h) *Final mixing ratio (r), dew-point (T_d) and lifting condensation level*. Read off Z to the nearest hundredth from the nomogram. The final mixing ratio is given by $r = r_0 + Z(r_s - r_0)$. Write down the corresponding surface dew-point T_d as determined from a tephigram. The final LCL is given approximately by $120(T - T_d)$ metres or $400(T - T_d)$ feet.

Notes: (1) When N (Table I) is much different from 1.40, the nomogram can still be used if s is multiplied by $N/1.40$. This elaboration will rarely be necessary near the British Isles.

(2) If the sea temperature is very variable the procedure may have to be carried out on two or more segments serially.

(3) Slightly greater accuracy may be achieved by successive approximation, using the calculated LCL, but this will rarely be worth while.

Conclusions. The method presented in this paper for forecasting coastal temperatures in cold-air advection with onshore winds appears to perform rather better than Blackall's method, though giving no real improvement in showery northerlies. Businger's method for forecasting dew-points gives coastal values which are too low, often by about 2 degC , but it should be useful for forecasting dew-points some way inland.

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APPENDIX I—SYMBOLS

c_p	specific heat of dry air at constant pressure
C_E	water-vapour transfer coefficient
C_H	heat-transfer coefficient ($= H/c_p \rho V (T_s - T)$)
d	depth of convection over the sea (mb)
E	upward evaporative flux of water vapour above the sea
g	acceleration due to gravity
H	upward flux of sensible heat above the sea

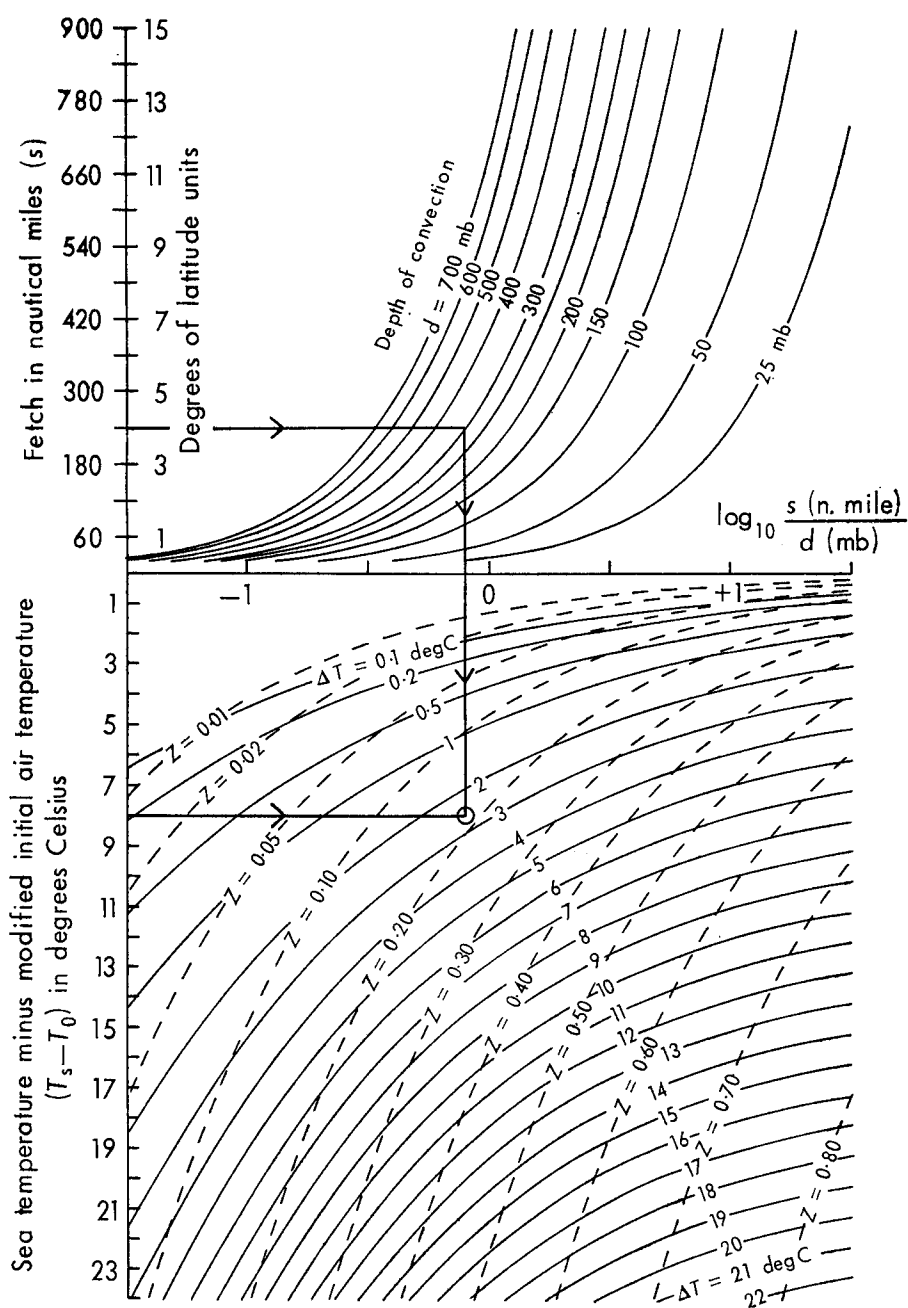


FIGURE 3—NOMOGRAM FOR DETERMINATION OF ΔT FROM s , d , AND $T_s - T_0$

Isopleths of ΔT —

Isopleths of Z ---

$T = T_0 + \Delta T$

$r = r_0 + Z(r_s - r_0)$

p_s	mean sea-level pressure along trajectory
r	humidity mixing ratio of air near surface
r_o	modified initial mixing ratio
r_s	saturation mixing ratio at temperature T_s
R	gas constant for air
s	sea fetch; length of completed trajectory over sea
t	time of sea crossing (s/V)
T	surface air temperature at sea or on coast downwind of sea
T_o	modified initial surface air temperature
T_d	dew-point of surface air at sea or near coast downwind of sea
T_s	sea surface temperature
\bar{T}	average value of T along track
V	average speed of cold air
Y	$(T - T_o)/(T_s - T_o)$
Z	$(r - r_o)/(r_s - r_o) = 1 + \frac{1 - Y}{Y} \ln(1 - Y)$ according to Businger ³
α	power of $(T_s - T)$ in expression for C_H
β	dimensionless coefficient in expression for C_H
ρ	air density near sea surface

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AN IMPROVED SATELLITE NEPHANALYSIS

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Summary. Standard satellite nephanalyses have certain limitations which suggest that an improvement in the present procedure would be useful. From these limitations and a list of the requirements of a nephanalysis procedure, an improved satellite nephanalysis on three layers is derived which increases the information content to between three and five times that of the standard nephanalysis, provides a defined set of operational guidelines for the analyst, and allows for a wider range of forecasting and archival usages.

Introduction. Satellite visible imagery presents a rich array of weather information to the user. For many purposes a summary of this information is adequate, for example a snapshot summary for forecasting purposes, or accumulated totals and their dependent means for climatological purposes. Satellite nephanalyses represent a summary over space of the salient features of a cloud field, using a discriminant analysis-classificatory form to subdivide an area on the basis of its cloud characteristics (cloud type, percentage cloud cover, etc.).

Although several attempts have recently been made to produce objective nephanalyses by computer (Decotiis and Conlan,¹ and Shenk and Holub²), there appears to have been little change in the procedure for hand-drawn nephanalyses since the mid sixties (Godshall³). Despite minor variations,* the standard nephanalysis code employed in the United Kingdom Meteorological Office is that operated by the former U.S. Weather Bureau, and discussed more fully in Barrett.⁴ This, in turn, is essentially an adaptation of the pre-satellite nephanalysis, defined as 'the study of synoptic charts on which only clouds and weather are plotted' (Berry *et alii*⁵), and issued to provide an input

* For example the anticyclone symbol (U.S. Weather Bureau) = the cold pool vortex symbol (U.K. Meteorological Office).

to the forecasting services. Observations plotted on the pre-satellite nephanalyses were as follows: cloud type, cloud amount, precipitation, weather, cloud ceilings and cloud-top heights. Of these, only the first two could be included in satellite nephanalyses, although areas *thought capable* of precipitation are outlined as 'synoptically significant'. Several other characteristics (e.g. size of features, jet-stream location, striations) have since been added.

Limitations of standard nephanalyses. Several authors have found that nephanalyses provide a useful data source for cloud studies, especially in conventional data-sparse regions. Such studies have been both direct, e.g. temporal cloud summaries (Sadler⁶), and indirect, e.g. the relative probabilities and intensities of rainfall (Barrett^{7,8}). Even towards the end of the 1960s, nephanalyses provided 'the only source of global data from the weather satellites containing quantized cloud information' (Clapp⁹). The standard nephanalyses do, however, contain certain inadequacies, and some of the more pertinent ones may be outlined as follows:

- (a) No rules governing the steps to be followed in constructing the nephanalysis have been established. This has resulted in a variation in nephanalysis procedures from country to country and from one analyst to another.
- (b) Only four cloud-cover categories—'Open', 'Mostly Open', 'Mostly Closed' and 'Closed'—are recognized. Of these, two have ranges of 20 per cent and two have ranges of 30 per cent.
- (c) 'Synoptically significant' cloud areas are outlined totally at the discretion of the analyst, without reference to any advisory guidelines.
- (d) Cloud-type recognition is concentrated on a distinction between stratiform and cumuliform clouds. It is indisputable that cumulonimbus and cirrus are rarely identified as such in middle latitudes, whilst stratocumulus is under-represented on the charts in both low and middle latitudes.
- (e) There is no established minimum-size reference giving guidance as to which cloud patterns to include in, and which to exclude from, the nephanalysis.
- (f) Detail on variations of cloudiness at the 'meso' scale (e.g. squall-lines, convective-cloud patterns) is sparse.
- (g) Conventional symbols are employed even though data from a new source and a new view are being considered.

Requirements of an improved nephanalysis procedure. Many of the criticisms that can be levelled against the standard nephanalysis arise because it is produced essentially as an aid to synoptic-scale forecasting. The general information content is consequently lower than the users of nephanalysis archives would like to see. In particular, it seems that any improved nephanalysis scheme should include more details of the cloud field at both the 'macro' and 'meso' scales, so that it will be of more general use rather than simply an aid to forecasting. This is particularly important in the developing countries where conventional observations are sparse, and in oceanic areas where there are relatively few island stations. In such areas more detailed nephanalyses could provide much information otherwise unavailable, for example for reasons of cost or inaccessibility.

Before we propose appropriate improvements to the practice of satellite nephanalysis a number of objectives may be identified. These include the following:

- (a) The nephanalysis information content should be as accurate and as complete as possible, within stated constraints of scale.
- (b) The chart must be clear and readily understandable, irrespective of the degree of detail that it contains.
- (c) The satellite-image interpretation procedure should be standardized to minimize operator variance.
- (d) The scheme should be capable of completion in operational circumstances within one hour.
- (e) The system should be sufficiently flexible, (1) for use over areas of different size and (2) for application of the results to a range of secondary problems.

The improved nephanalysis scheme outlined below seeks to meet these requirements, visible images being used initially as the data base.

The improved nephanalysis. An increase in the amount of information portrayed on an improved nephanalysis raises the problem of clarity: how can the desired level of detail be achieved without forfeiting the simple, immediate visual impact of the standard nephanalysis? A first step towards solving this basic problem involves defining the type of analysis performed on the satellite imagery. This can take one of two forms: (a) a description of the cloud field, and (b) an interpretation of the cloud features present. If these procedures are separated, nephanalysis may be carried out more easily by distinguishing between the two methods employed. An example serves to illustrate the point. A roughly circular cloud feature of 6 degrees of latitude in diameter in the Indian Ocean, with more than 90 per cent of cloud cover (mainly cumulonimbus and cumulus congestus cloud types, and striations spiralling towards a central clear area), is a *description* of the appearance of a tropical storm from satellite altitudes. It is the *interpretation* of this cloud area which defines it as a hurricane.

We propose that description and interpretation of cloud fields be separated both in stage of execution and in mode of presentation. Since description is the easier task to undertake, we suggest further that a three-layered nephanalysis, comprising two descriptive layers and one interpretative layer, would be even better. This readily permits an increase of some 3-5 times in the information content compared with the standard nephanalysis. The format of this improved nephanalysis comprises:

- (a) a base layer on opaque paper giving details of the geography and cloud cover,
- (b) a transparent overlay carrying information on cloud type and cloud structure, and
- (c) a second transparent overlay depicting an interpretation of features of the cloud field.

The stages to be followed in constructing this improved nephanalysis are summarized in Figure 1, and an example of its operation is given in Figure 2 (an improved nephanalysis derived from the ESSA 9 satellite imagery for 3 February 1970 shown in Plate I).

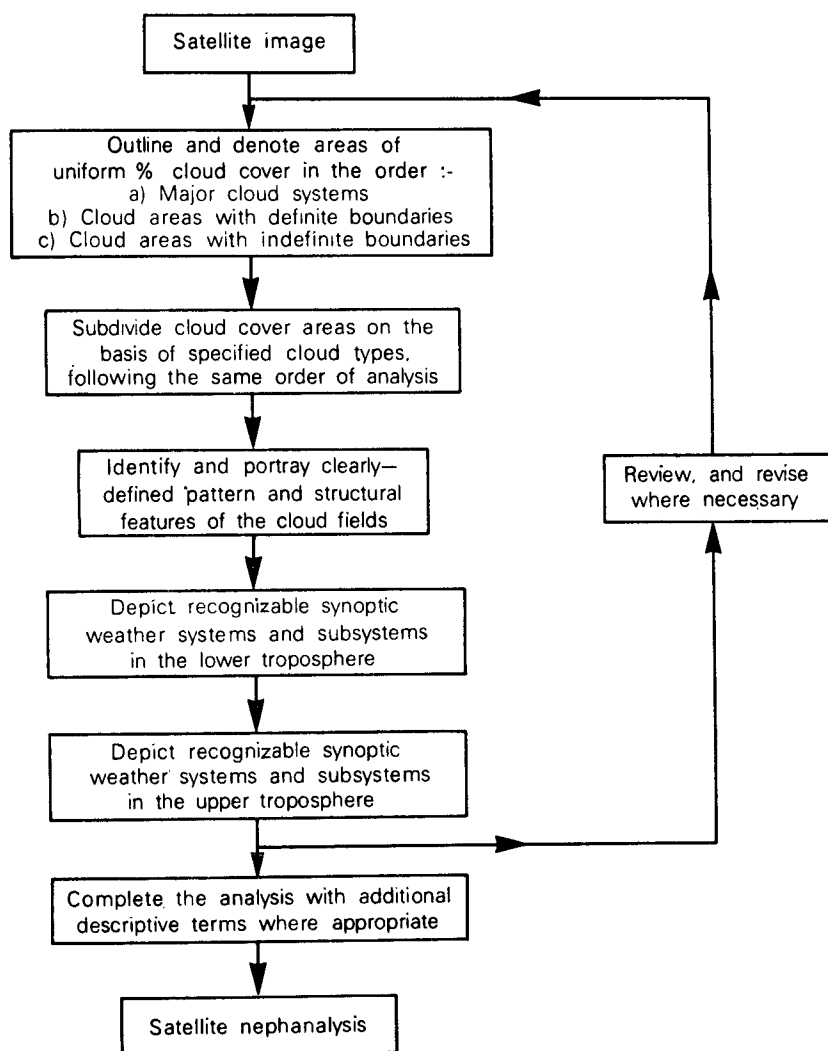


FIGURE 1—STAGES IN THE CONSTRUCTION OF AN IMPROVED SATELLITE NEPHANALYSIS

Description of the cloud field is the first method of analysis applied to the satellite photograph. The results comprise the lower two layers as follows:

- (a) The spatial distribution of cloud cover is represented by an areal density shading on layer 1 (Figure 2a). For this purpose, five equal classes of percentage overcast are used (see Figure 2d). These five intervals replace the previous four, thereby providing more scope for detailed depiction of the cloud cover. An added advantage is that each class possesses the same range (i.e. 20 per cent). Areas of uniform cloud amount are outlined in the order suggested in Figure 1, firstly definite and secondly indefinite systems, both bordered by solid lines. The

suggested minimum-size constraint operates on the basis of an area equivalent to a $2\frac{1}{2}$ -degree square, so no features larger than this should be omitted from the nephanalysis. All single linear features of more than 5 degrees of longitude or latitude in length should be included.

- (b) Cloud type and cloud structure form the bases for the second set of descriptive characteristics, and are represented in symbolic form on the first of the transparent overlays (Figure 2b). Accurate recognition of cloud type is a major problem in nephanalysis so the standardization of recognition procedures is imperative. The scheme suggested by Anderson¹⁰ of identifying clouds from their brightness and texture characteristics provides a set of operational guidelines suitable for such a standardization. Where cloud type varies within an area of the same cloud amount, dashed lines are used to depict this change rather than the solid-line boundaries used for cloud cover. The remaining descriptive features on the second layer are size of clouds and open spaces, and cloud pattern and shape. The symbols for these features are given in the key for the improved nephanalysis in Figure 2d.
- (c) The interpretation of the cloud field is the final layer of the improved nephanalysis set (Figure 2c), and involves the identification of the features described in the lower two layers and other associated phenomena. In compiling the list of interpretation features shown in Figure 2d, information was drawn from the ESSA *Technical Report* entitled 'Application of meteorological satellite data in analysis and forecasting' (Anderson *et alii*¹¹), which contains a comprehensive appraisal of the cloud features normally found on satellite visible imagery. One significant addition to the list is the identification of cloud-top height, which is determined from the brightness, cloud type and synoptic situation of a given area. The cloud-top height is then placed in one of three simple categories—high (above 6 km), middle (2–6 km) or low (below 2 km) (Berry *et alii*⁵)—and portrayed appropriately (Figure 2d).

Any combination of these three layers can be used to give the required level of information for a particular *purpose*. For example, cloud cover (layer 1) and cloud type (layer 2) can be used for climatological applications (especially in weather bureaux where the forecasting programme is predominantly numerical), and all three layers for synoptic forecasting (especially where more traditional forecasting procedures are followed).

As the improved nephanalysis is a free-hand technique, the charts can be completed within one hour for 'real-time' operational use in synoptic forecasting. The optimum arrangement of the three charts at the central forecasting/automatic picture transmission facility is for flanking charts to be printed in reverse on transparent material, so that they can be folded in to overlay the others. For facsimile transmission to regional weather centres and other users the three charts could be transmitted side by side.

Standard and improved nephanalyses: a concluding note. The improved nephanalysis introduced in this paper is an attempt to fulfil the requirements of a nephanalysis procedure listed above by increasing the information content and standardizing the rules for the preparation of the nephanalysis. The sectionalized format of this new chart is the most significant contribution to the increase in the amount of information presented to the

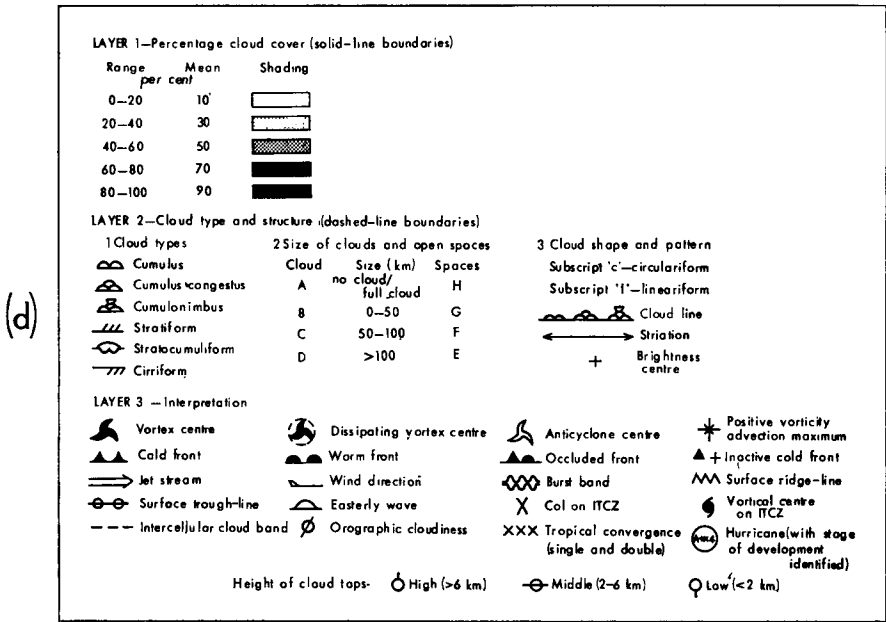
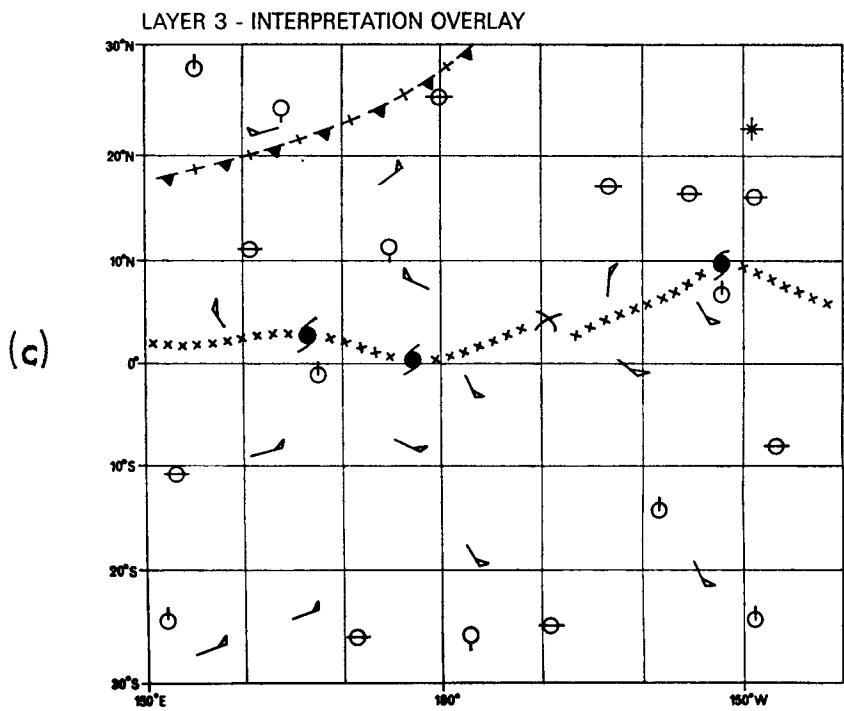


FIGURE 2—continued

(c) interpretation overlay

(d) key to the improved nephanalysis scheme

user. In addition, the fuller list of descriptive and interpretative features (Figure 2d) gives greater scope for an analysis in detail down to the 'meso' scale. The separation of (a) the method of analysis, and (b) the different types of information shown on each layer, gives clarity to the stages followed in an analysis of satellite imagery, and with this flow-chart of procedures firmly laid down, subjective assessment and operator variance are minimized.

Visible imagery only is considered in the improved nephanalysis scheme presented here. However, an extension of the data sources to include infra-red imagery would be useful for increasing the information content and frequency of coverage provided by nephanalyses. Our work at Bristol University is directed now towards the development of a nephanalysis scheme for infra-red imagery. The biggest problem involves the diurnal temperature changes at the earth's surface and in the lowest layer of the atmosphere. The biggest advantage stems from the twice-daily reception of the images from the satellite. It is to be hoped that the analytical techniques which we are designing to be applied by cheap objective means may be applicable either to infra-red or to visible satellite images. Such developments must await the future, but it can be affirmed now that by using infra-red and visible imagery together, improvements in our analysis of satellite imagery will follow.

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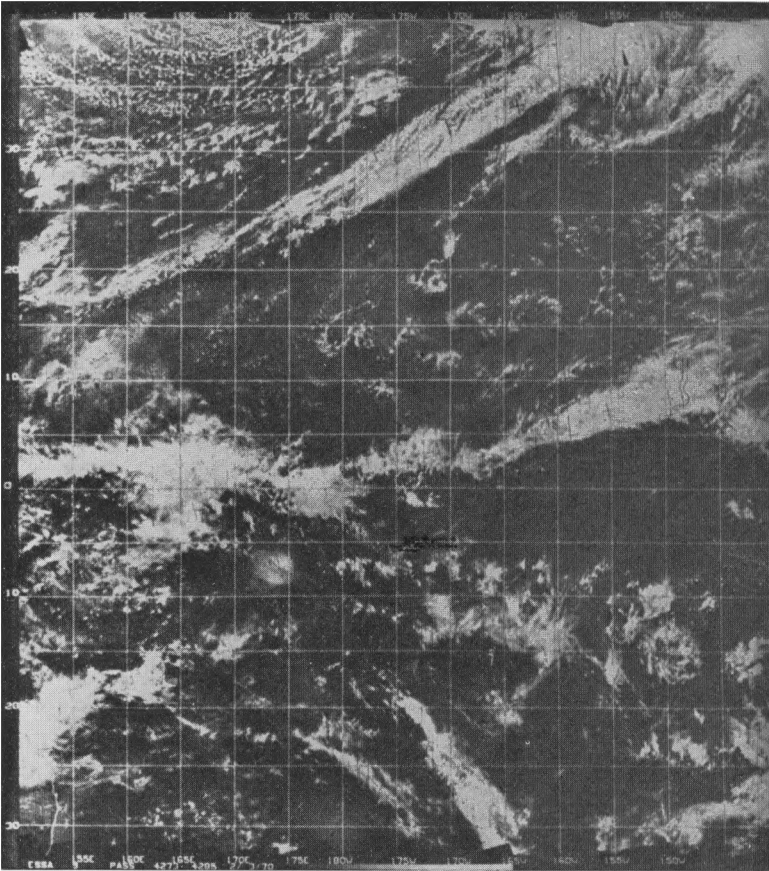


PLATE I—ESSA 9 COMPUTER-RECTIFIED MERCATOR MONTAGE OF THE CENTRAL PACIFIC, 3 FEBRUARY 1970



PLATE II—METEOROLOGICAL OFFICE EXPERIMENTAL SITE, BEAUFORT PARK, NEAR BRACKNELL

General view showing the exposure of radiation instruments on the roof of the main building.

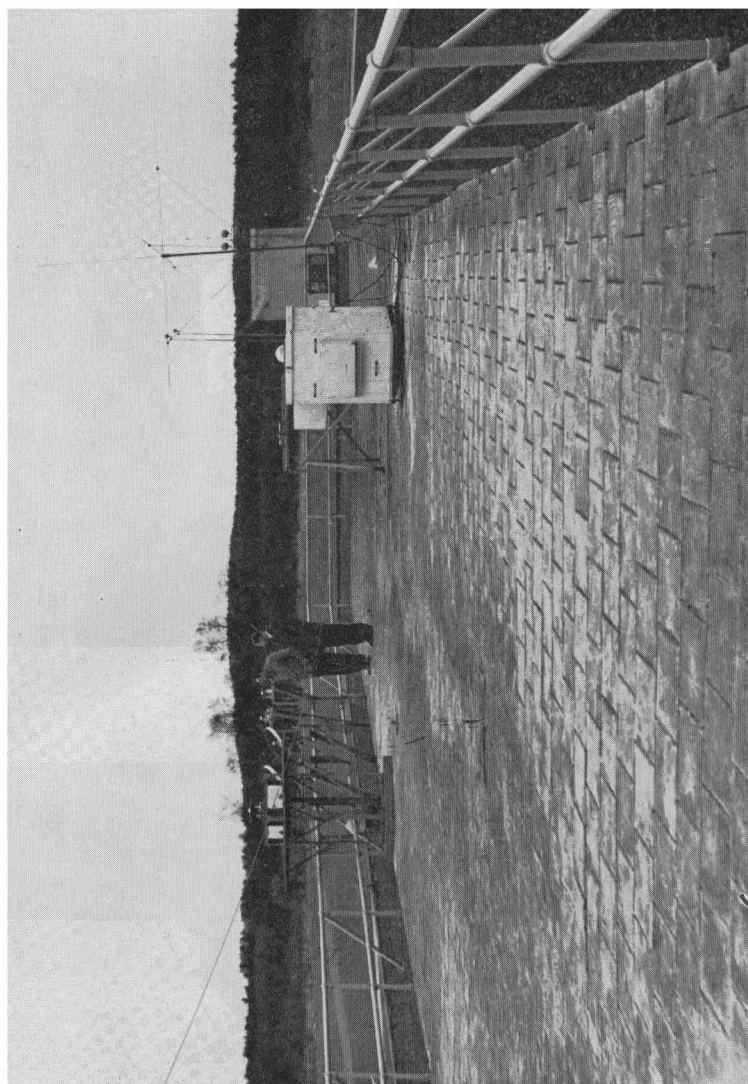


PLATE III—METEOROLOGICAL OFFICE EXPERIMENTAL SITE, BEAUFORT PARK, NEAR BRACKNELL
Another view of the radiation instruments on the roof of the main building.

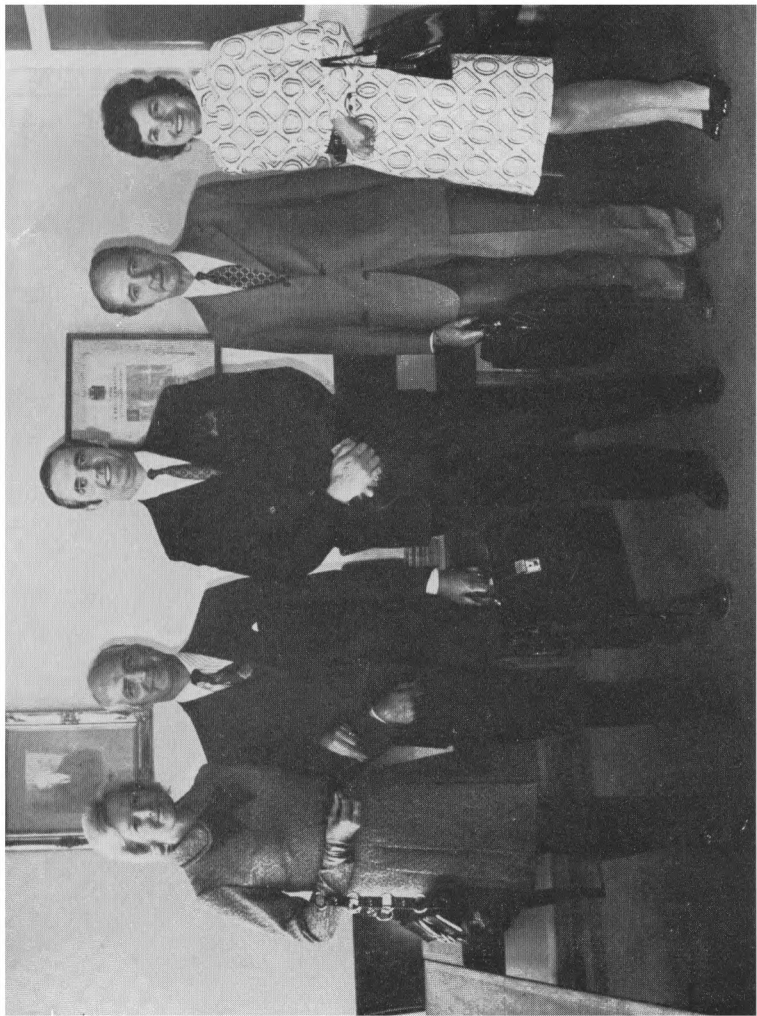


PLATE IV—AWARDS TO CIVIL AIRLINE PILOTS

From left to right: Mrs D. H. F. Banton, Captain D. H. F. Banton, Director-General of the Meteorological Office, Captain and Mrs K. Mountney (see page 28).

551.509.324.2

FORECASTING CONVECTIVE THUNDERSTORMS, HAIL AND SHOWER ACTIVITY IN THE MIDLANDS

By N. J. ATKINS

Summary. The parcel method, found to be widely used by forecasters because of its success compared with other techniques, was used in an investigation of convective activity in the Midlands. It is shown that, in addition to the depth of the convective layer, the amount of potential energy in the lower part of the layer shown on a tephigram can be used to determine the intensity of shower activity. An extension to the parcel method is therefore suggested in this paper.

Introduction. The Saunders¹ test of thunderstorm forecasting showed that 'general practice' gave better results than other techniques, and it was possible with help from several forecasters to determine what the 'general practice' was. Of the 26 forecasters who completed a questionnaire, 24 used the parcel method, and 10 of them used it in conjunction with another technique, which for seven of them included the slice method. Fourteen forecasters examined the size and shape of the positive area as given by the parcel method, but their reasons for doing this were too varied to be classified. It was decided therefore to analyse the relationship between weather reported and the data obtained from the parcel method, including the size and shape of the positive area shown on a tephigram. The completed questionnaire also showed that none of the 26 forecasters eliminated thunderstorms from a forecast because of the possible entrainment of dry air from the environment, but that the degree of such entrainment was used to judge whether convective activity would be widespread, scattered or isolated. During the present investigation, the water-vapour content of the two layers, 1000 to 700 mb and 1000 to 850 mb were analysed, and also the dew-point separation for the same two layers, but no useful result was obtained.

Period and area of the investigation. Five observing stations in the Midlands, namely Cardington, Wittering, Shawbury, Watnall and Elmdon (see Figure 1) grouped together in the *Daily Weather Report* were used for the four-year period from 1970 to 1973 inclusive. There are no radiosonde stations in the Midlands but normally the ascent from one or more of the nearest four stations (also shown in Figure 1) provided a representative temperature sounding.

Shape and size of the positive area (E). A quick method was required to assess the shape and size of the positive area as given by the parcel method using the forecast maximum temperature and the forecast dew-point at the time of this maximum temperature. It was found that the areas could be represented by the sum of the separations of the parcel and environment curves taken at 50-mb intervals, and that it was quicker to measure them with a scale of millimetres than to express them in degrees read from the tephigram. Measurements were made on Metform 2810, and it would be necessary to make a conversion if a differently scaled tephigram were used. (The scale of

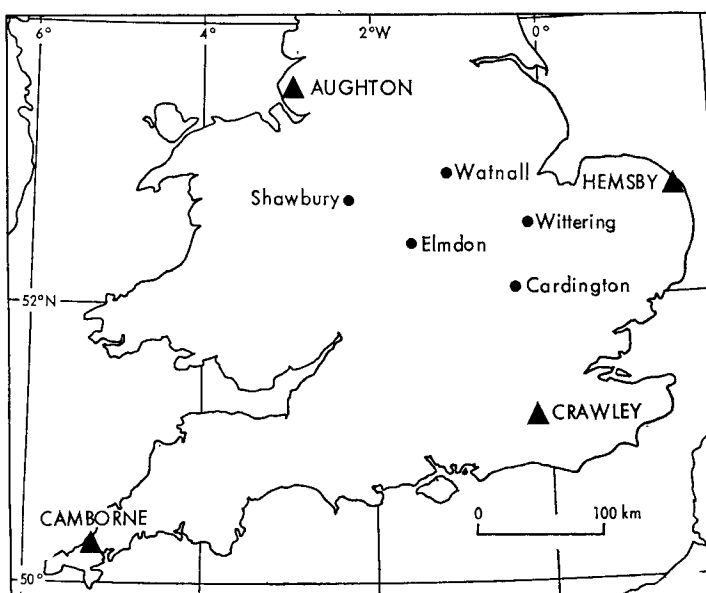


FIGURE 1—MAP SHOWING THE LOCATION OF THE FIVE REPORTING STATIONS IN THE MIDLANDS USED IN THE INVESTIGATION OF SHOWERS AND THUNDERSTORMS. The positions of the nearest four radiosonde stations (▲) are also shown.

Metform 2810 used is 10 degC = 52 mm and the energy equivalent is $9.4 \times 10^{-2} \text{ J cm}^{-2}$.) The area was classified into one of three types:

- (a) with a low centre of gravity,
- (b) with a high centre of gravity, or
- (c) with a central centre of gravity.

The positive area was divided into a lower part (E_L) and a higher part (E_H), and the classifications were made by comparing the areas. The level at which the area was divided was defined as the arithmetic mean of the surface pressure and the pressure where the parcel cut the environment curve. A measure of the degree of elongation of the positive area was made by linking it with the depth of instability at the saturated adiabatic lapse rate (SALR). Hamilton² has shown that the depth of instability at the SALR is a useful guide to shower activity.

Weather distribution diagrams. The weather reported at five Midland stations was related on distribution diagrams to the depth of instability at the SALR, to the size of the positive area, and to the size of the partial areas E_L and E_H . These were obtained from the most representative midday temperature sounding. The weather reported was taken from the five stations as a whole so that hail at one station and a thunderstorm with rain at another was classified as a thunderstorm with hail. Occurrences of snow were included as rain, and different symbols were allocated to the following weather classifications: (a) nil or slight shower, (b) moderate shower, (c) heavy shower,

(d) moderate hail shower, (e) heavy hail shower, (f) thunderstorm with rain, (g) thunderstorm with hail, and (h) thunderstorm with heavy hail. It was necessary to include every convection day during the four-year period and for the purpose of this work a convection day is defined as one on which convection would be expected to rise above 900 mb—there were 693 such days. All three diagrams showed an increase of shower intensity with increasing depth of instability at the SALR. There was also a trend for shower intensity to increase with increasing positive area, E , but this was most noticeable in the diagram which used E_L , the lower part of the positive area. This showed that at a constant depth of instability the intensity of weather reported was to a large extent proportional to E_L . Even so it was difficult to draw boundary lines on the diagram owing to the occurrence of several polar-air thunderstorms with relatively shallow instability depths. The diagram was therefore split into two, thereby separating the 'cold' days when the height of the 0°C isotherm was below 850 mb from the 'warm' days when the 0°C isotherm was at or above 850 mb; these two diagrams are illustrated in Figures 2 and 3. For the sake of clarity, occasions of nil or slight showers have been omitted from the diagrams—there were 411 such occasions. If they had been plotted they would mostly have occurred towards the origin of the diagram.

Hail. It is probable that hail reached the ground in places in the Midlands other than the five stations used in the investigation on most days when thunderstorms with rain only were reported. The chance of hail falling at one particular place, however, increases with the lowering of the 0°C isotherm and also with increasing E_L . This is shown in Figure 4 which used all convection days when the depth of instability at the SALR was 200 mb or more with the occasions of nil or slight showers again being omitted.

Conclusions. Consideration of the models of hailstorm clouds as illustrated on page 159 of Ludlam,³ and in Hitschfeld,⁴ led to the working hypothesis that the strength of the updraught in the lower part, which must exceed a critical value to accelerate the hailstones upward sufficiently to carry them into the higher part, was likely to be more important and critical than that in the higher part. Hence the positive area given by the parcel method on a tephigram was able to provide additional information by virtue of the size of its lower portion and shape.

Method. (See example in Figure 5.)

(a) On a representative temperature sounding, modified for midday, use the non-superadiabatic maximum temperature and dew-point at the time of this maximum temperature, and draw in the parcel path from the surface pressure (P_1) up to the point where the parcel and environment curves meet (P_3).

(b) Mark in the mid point of the convection layer obtained by putting $P_2 = \frac{1}{2}(P_1 + P_3)$.

(c) Starting at 950 mb measure in millimetres the separation between the parcel and environment curves at every 50-mb interval up to P_2 . If P_2 falls within ± 10 mb of a 50-mb multiple, then the measurement at the latter level is halved and included in the total to obtain E_L .

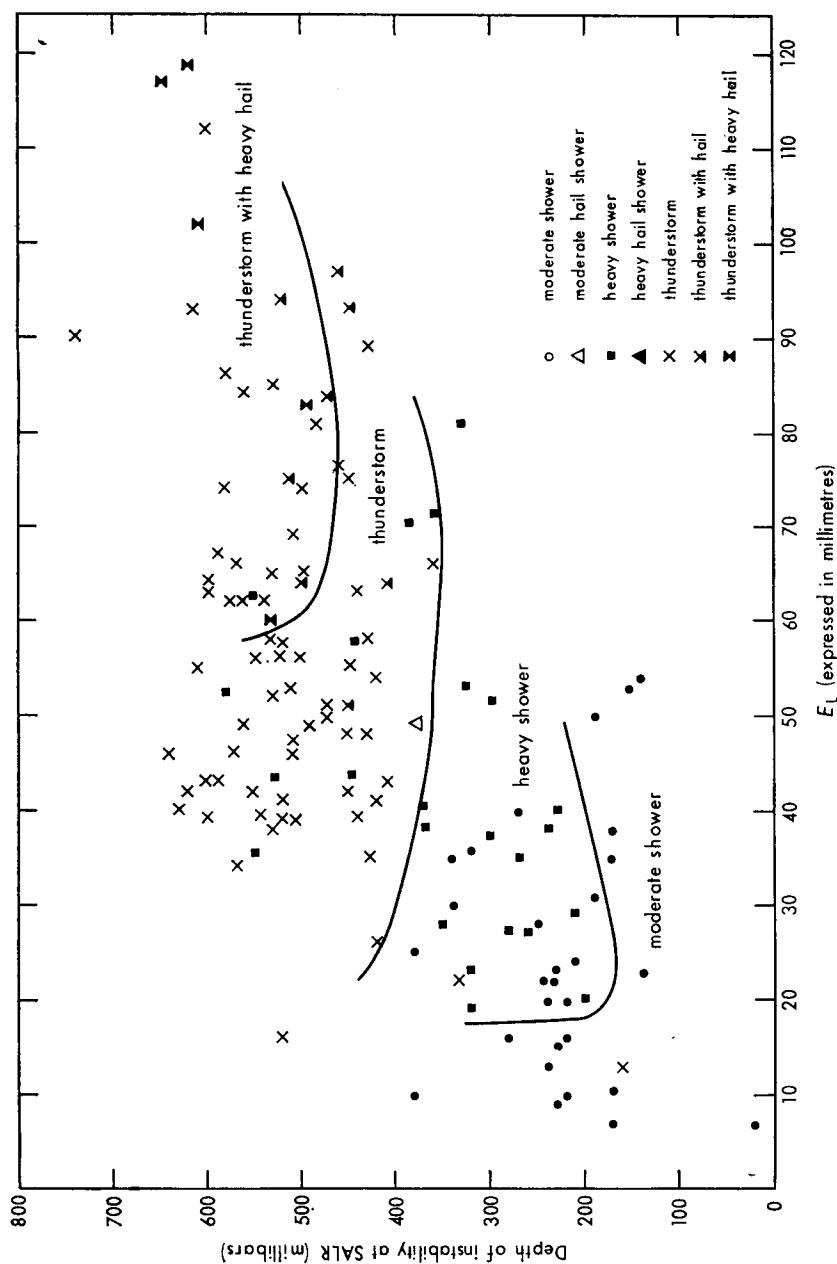


FIGURE 2—OCCURRENCES OF MODERATE AND HEAVY SHOWERS, HAIL AND THUNDERSTORMS ON CONVECTION DAYS WHEN THE 0°C ISOTHERM WAS AT OR ABOVE 850 mb FOR 1970-73 INCLUSIVE
The symbol for 'moderate shower' in the key should be ●

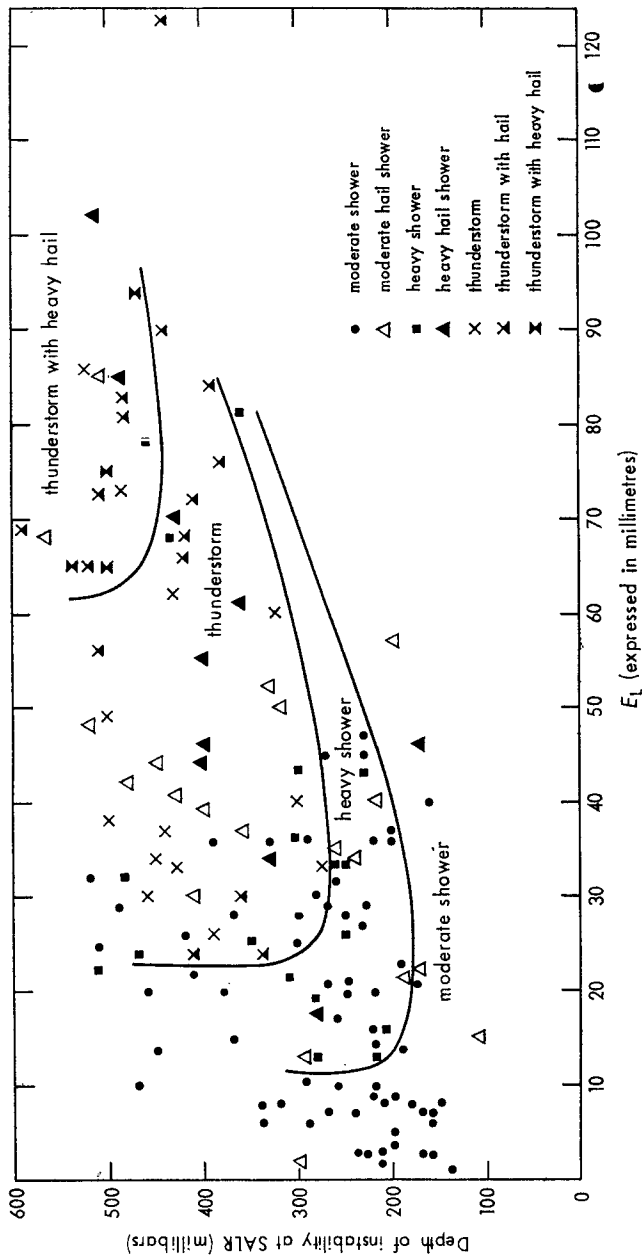


FIGURE 3—OCCURRENCES OF MODERATE AND HEAVY SHOWERS, HAIL AND THUNDERSTORMS ON CONVECTION DAYS WHEN THE 0°C ISOTHERM WAS BELOW 850 mb FOR 1970-73 INCLUSIVE

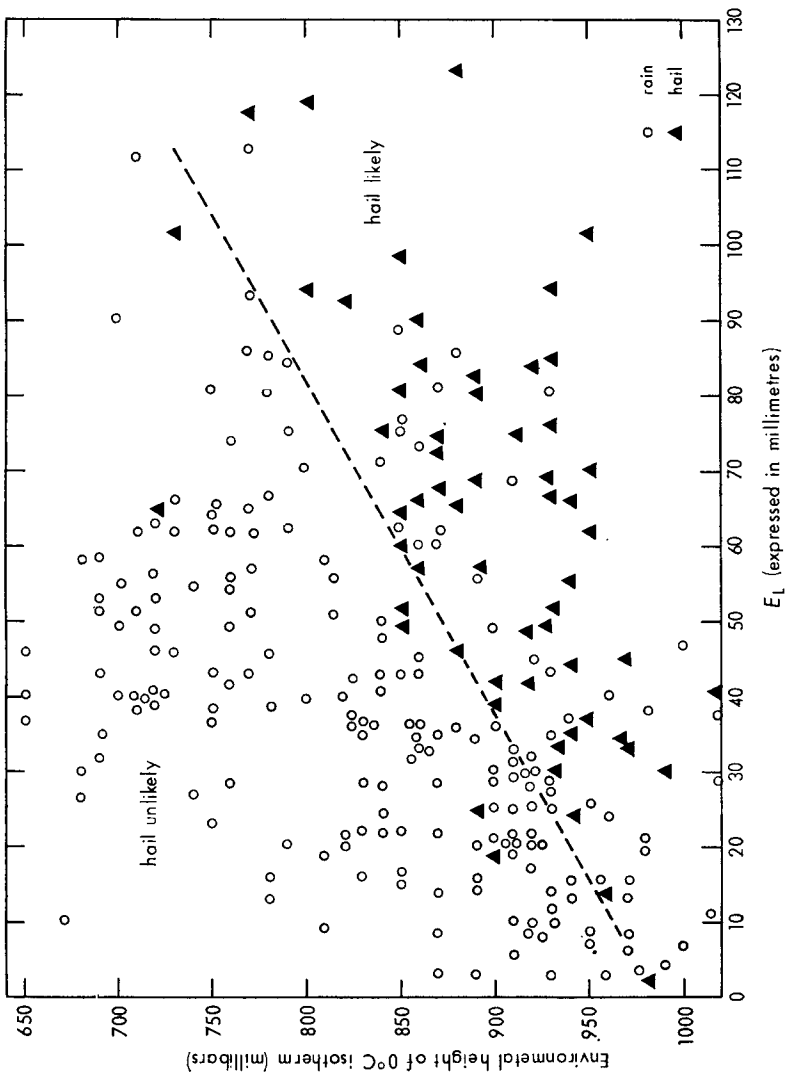


FIGURE 4—OCCURRENCES OF MODERATE AND HEAVY RAIN OR HAIL ON CONVECTION DAYS WHEN THE INSTABILITY DEPTH AT THE SATURATED ADIABATIC LAPSE RATE WAS EQUAL TO OR GREATER THAN 200 mb FOR 1970–73 INCLUSIVE

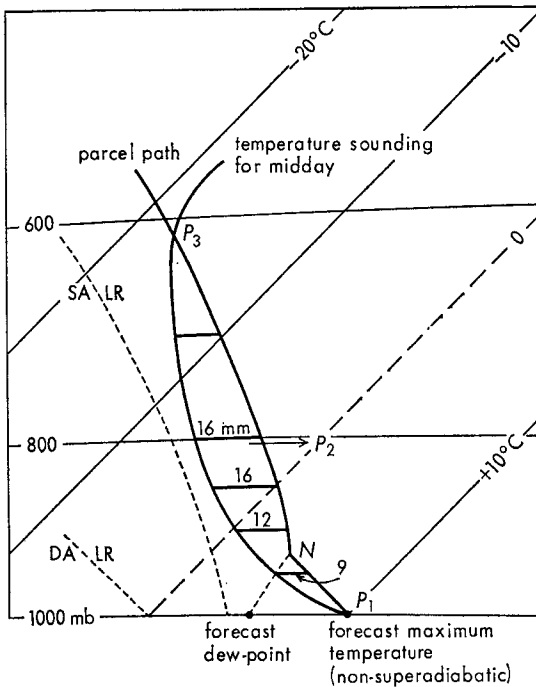


FIGURE 5—AN EXAMPLE OF THE SUGGESTED EXTENSION TO THE PARCEL METHOD

P_2 (805 mb) is the arithmetic mean of the surface pressure P_1 (1000 mb) and the pressure where the path curve for the parcel cuts the environment curve at P_3 (610 mb). E_L is the sum of the measured separations at 50-mb intervals between the two curves from 950 mb up to P_2 .

If P_2 falls within ± 10 mb of a 50-mb multiple, the measurement is halved and included in the total. In this example (a) $E_L = (16/2) + 16 + 12 + 9 = 45$ mm, (b) the instability depth at the SALR is $930(N) - 610 = 320$ mb and (c) the height of the 0°C isotherm is 895 mb. From Figures 2 and 4 of this article, thunderstorms with hail would be forecast.

(d) Obtain depth of instability at the SALR, i.e. $N - P_3$ mb (N is the condensation level).

(e) Use values from (c) and (d) above to find the expected convection weather from either Figure 2 or Figure 3, depending on the height of the environmental 0°C isotherm. An indication of the chance of hail will be given by E_L and the height of the 0°C isotherm by using Figure 4.

Acknowledgement. The writer wishes to thank those forecasters at London Weather Centre, Watnall, Bawtry, Scampton, Wyton, Marham, and Cottesmore, who kindly completed the questionnaire on their method of forecasting thunderstorms.

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551.589.1(492):519.2

A BIENNIAL CYCLE IN THE NUMBER OF FINE DAYS IN THE NETHERLANDS

By C. J. E. SCHUURMANS

(Koninklijk Nederlands Meteorologisch Instituut, De Bilt, The Netherlands)

Summary. A statistical study is made of daily weather types at De Bilt over the period 1881–1972 which demonstrates the existence of a biennial cycle in the occurrence of warm, dry, and sunny weather from late spring to early autumn.

Introduction. In 1967 Davis¹ published an article on the summers of north-west Europe. In this article he presented some good evidence of the existence of a biennial cycle in north-western European summers—summers of the odd years being generally better than summers of the even years. The study was mainly based on seasonal means of daily maximum temperatures for seven stations in the British Isles and some 30 continental stations including De Bilt, The Netherlands. The temperature records studied varied from 30 to 90 years, the record for De Bilt comprising 65 years.

In Davis's study, for each station χ^2 -values are computed for the contingency tables, giving the frequencies of summers with mean daily maximum temperatures higher or lower than the preceding summer for odd and even years separately. In Figure 1 of the article which is reproduced here, these χ^2 -values are plotted and analysed according to the significance level. From this figure it is concluded that the biennial cycle is best developed over the British Isles, southern Scandinavia and large parts of France, western Germany and Austria. The χ^2 -value for De Bilt by no means reaches the 5 per cent level of significance, which led the author to draw an isopleth of $\chi^2 = 3.84$ (5 per cent level of significance) around the southern North Sea and its bordering areas thus creating an isolated region for which the biennial cycle is not in evidence.

The present paper presents the result of a statistical study of daily weather types at De Bilt over the period 1881–1972. It is shown that the biennial cycle of summer weather is also in evidence at De Bilt.

Weather types. Weather types have been defined in such a way that daily mean temperature, amount of precipitation and duration of sunshine determine the weather of a given day at a given place.

The frequency distribution of daily mean temperature for a certain day over 90 years has been subdivided into terciles. The lowest tercile is called 'below' (B), the middle 'normal' (N) and the highest 'above' (A). Daily precipitation amounts and relative duration of sunshine (per cent) have also been subdivided into three classes, but with fixed class limits, namely for precipitation: dry (D) is less than 0.3 mm, moderate (M) is 0.3–4.9 mm and heavy (H) is 5.0 mm or more; for sunshine: 25 per cent or less is cloudy (C), 26–49 per cent is partial (P) and 50 per cent or more is sunny (S).

Combinations of (B,N,A), (D,M,H) and (C,P,S) define 27 weather types. The frequency of occurrence of the various types varies from very frequent (some 15 to 20 per cent of all days in a certain season) to very rare (less than 1 per cent). Most of the types show a rather large annual variation.

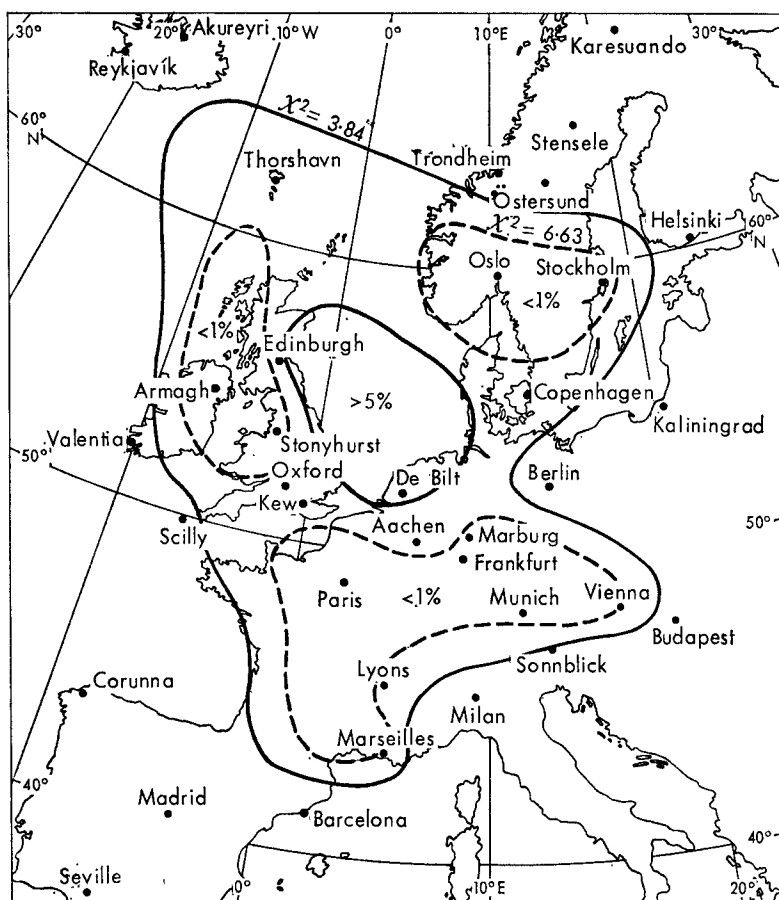


FIGURE 1—APPROXIMATE ISOPLETHS OF 1 PER CENT AND 5 PER CENT LEVELS OF SIGNIFICANCE OF χ^2

(After Davis;¹ see text.)

Weather types have been determined for De Bilt for each day from 1 January 1881 onwards.² We shall only consider here the weather type ADS—warm, dry and sunny weather.

Fine days in summer. The number of fine days (ADS-days) in summer (June, July and August) at De Bilt shows a rather large interannual variation. For the period 1881–1972 these numbers are given in Table I. The number of ADS-days varies from 1 (in 1907, 1918 and 1962) to 51 (in 1947).

The values in Table I have been added for odd and even years separately. It turned out that the summers of the odd years had on the average about 4 (or 27 per cent) more ADS-days than the summers of the even years.

Statistical significance. Various statistical tests have been applied in order to investigate the statistical significance of the phenomenon.

TABLE 1—THE NUMBER OF ADS-DAYS IN SUMMER (JUNE, JULY, AUGUST) FOR THE PERIOD 1881-1972

	0	1	2	3	4	5	6	7	8	9
188-	—	21	8	17	31	16	20	25	10	26
189-	15	9	11	24	10	20	23	23	12	29
190-	24	26	17	6	20	18	17	1	14	7
191-	12	30	15	9	27	7	9	16	1	17
192-	10	26	5	18	11	19	12	9	11	16
193-	19	9	29	31	25	28	19	20	14	23
194-	18	24	20	15	16	19	9	51	18	21
195-	20	9	14	16	5	22	3	16	12	30
196-	11	11	1	12	20	9	12	16	15	23
197-	24	18	7							

According to 'Student's' t -test the difference between the mean values for odd and even years is significant at nearly the 1 per cent level ($t = 2.39$). On applying the parameter-free rank-sum test, which is more widely applicable than the t -test, it was also found that the hypothesis of the two samples of odd and even years belonging to the same distribution can be rejected at the 3 per cent level. In the latter test the years are ranked according to the number of ADS-days. When equal numbers occurred, those years have been ranked simply in chronological order. This procedure does not affect the validity of the test. The rank-sum T_o for the odd years turned out to be 2417, which means that for the even years this sum (T_e) must be equal to

$$(N(N+1)/2) - 2417 = 1861 \quad (N = 92).$$

The expected T (μ_T) and its standard deviation (σ_T) are given by

$$\mu_T = \frac{N_1(N_1 + N_2 + 1)}{2} \text{ and } \sigma_T^2 = \frac{N_1 N_2 (N_1 + N_2 + 1)}{12}, \text{ where in the present}$$

case $N_1 = N_2 = 46$.

For $N_1, N_2 > 10$, T is normally distributed.

By comparison with the standard normal distribution it is found that with $T = 2417$ the area under the standard normal curve between 0 and

$$z = \frac{2417 - \mu_T}{\sigma_T} = 2.17$$

is 0.4850, from which we may conclude that the difference between T_o (or T_e) and μ_T is significant at the $1 - 2(0.4850) = 0.03$, or 3 per cent level.

Though Davis from his analysis of mean maximum temperatures could not find the biennial cycle to be in evidence at De Bilt, our analysis clearly shows that, for the indicated period, differences between summers of odd and even years did exist. A preliminary conclusion could furthermore be that Davis's study had its limitations as to the demarcation of areas influenced by the biennial cycle.*

* Davis's method of analysis has also been criticized on statistical grounds by P. B. Wright (*Met Mag, London*, 100, 1971, pp. 301-303).

Fine days over the year. As will be clear from the definition, fine days do occur mainly in summer. In the colder seasons of course DS (dry and sunny) more often goes with low (B) or normal (N) temperatures. Nevertheless, the numbers of ADS in spring and autumn are still large enough to analyse them for a possible extension of the biennial cycle into these seasons.

Table II gives for each month of the year the number of ADS-days for even and odd years separately.

TABLE II—THE NUMBER OF ADS-DAYS IN EACH MONTH FOR THE PERIOD 1881–1972

	Odd years	Even years	Difference
January	22	26	— 4
February	42	34	+ 8
March	114	132	— 18
April	192	184	+ 8
May	278	243	+ 35
June	280	244	+ 36
July	312	221	+ 91
August	266	211	+ 55
September	205	153	+ 52
October	94	79	+ 15
November	33	24	+ 9
December	8	17	— 9

It turns out that in the autumn, especially in September, the biennial cycle is still influencing the number of fine days. As far as spring is concerned the effect seems only to be present in May.

Synoptic-climatological considerations. It is of interest to compare these results with conclusions which can be drawn from the monthly patterns of the quasi-biennial pressure oscillation, published by Murray and Moffitt.³ From these patterns one may infer that from May to September anomalous high pressure occurs in odd years, as compared with the even years, over western to north-western Europe. This will cause in the season concerned more anticyclonic conditions over The Netherlands, accompanied by rather light winds varying in direction between north-east to east, and south. These circumstances easily explain the excessive occurrence of fine days.

In early spring and also in late autumn the pressure-difference patterns over Europe (still according to Murray and Moffitt) are quite different from those of the summer months. In general they are of such a nature that they would not favour more ADS-days to occur in odd years than in even years. When nevertheless, the figures in Table II suggest that the biennial effect is extended into late autumn, this could possibly be attributed to the fact that after good summers the North Sea is warmer than after less-good summers.

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REVIEW

Analytical methods in planetary boundary-layer modelling, by R. A. Brown. 200 mm × 140 mm, pp. xii + 148, *illus.*, Adam Hilger Ltd, Warner House, Folkestone, Kent, 1974. Price: £8.00.

This book cannot be recommended except perhaps as a means of gaining a general impression of current ideas on the origin and effect of vortex rolls in the boundary layer which arise from a vorticity and thermal instability of the quasi-Ekman layer velocity profile. These rolls occur quite frequently and can be important in determining the exact nature of the internal structure of the layer. The final third of the book is concerned with these instabilities, whilst the first two-thirds are devoted to a more general description of boundary-layer methods but with an eye very much on the needs of the final part.

The approach is a rather mathematical one, but the value of this is largely lost by a profusion of errors, some typographical, others more basic. For example on page 47 there are four errors in the space of four equations and one confusing bit of notation; on page 39, the basic equation, equation (4.3), is apparently hopelessly incorrect, and so on.

Even the physical concepts and arguments are often unacceptable. Section 5.2 on the surface layer is completely misleading; it implies that it is a *constant flux* layer (the fluxes actually fall off faster there than anywhere else in the boundary layer) and wrongly that its depth is comparable with the depth of the roughness elements z_0 (where the basic equations are in fact quite inadequate and therefore cannot be applied). The description of the physical reasons for the existence of vortex instability in the boundary layer—potentially the most interesting section of the book—is no help at all to the uninitiated and no source of admiration for those who do understand already.

The front cover is very attractive (showing a jet-stream cloud stretching across Egypt and Saudi Arabia (*not* Jordan!)). However, the reader has to search rather carefully to find those aspects relevant to the subject matter and the casual 'shopper' might be quite misled as to what this book is really about.

F. B. SMITH

NOTES AND NEWS

Meteorological Office awards to captains and navigators of civil airlines

Since 1954 awards have been made annually to encourage civil airline captains and navigators to make air reports. Suitably inscribed books are awarded to the captains and navigators who have provided the best series of reports during the year under review. Captains who have given long and meritorious service in the provision of air reports are considered for the award of brief-cases.

In 1974 brief-cases were awarded to Captain D. H. F. Banton, British Airways (Overseas Division), and to Captain K. Mountney, British Airways (European Division) by the Director-General at a ceremony held in the Headquarters of the Meteorological Office on 2 October (see Plate IV).

COVOS/COMESA Conference

A successful joint conference was held in Oxford on 24–26 September 1974 by the French COVOS (Comité sur les Conséquences des Vols Stratosphériques) and the British COMESA (Committee on the Meteorological Effects of Stratospheric Aircraft) groups which have been studying the possible environmental effects that might arise from the operation of large numbers of supersonic transport aircraft in the stratosphere, and the results of their research programme to date were discussed.

Co-operation in motorway fog studies

The Meteorological Office is co-operating with the Home Office, Transport and Road Research Laboratory and the Atomic Energy Research Establishment in a study which is related to fog on motorways. A Meteorological Office transmissometer has been set up alongside the M4 motorway near Theale, Berks., as a reference instrument for the evaluation of a number of cheaper and simpler visibility devices.

Hercules participates in GATE

The Hercules was delivered to the Meteorological Research Flight on 3 January. Before its departure for Dakar, Senegal, on 24 June, in order to participate in the GARP Atlantic Tropical Experiment of the World Meteorological Organization, about two months were spent on flight tests of the aircraft, two months on the installation of additional experimental instrumentation, and six weeks on flight testing experimental installations. During the first phase of GATE, the aircraft flew successfully on 10 missions of 8–10 hours duration each, in addition to three calibration flights. In general experimental instruments have functioned satisfactorily.

British infra-red detectors in NASA weather satellites

What have been described by the Goddard Space Center of the National Aeronautics and Space Administration as the first 1–1½-mile resolution pictures ever received from a weather satellite in synchronous orbit result from the development of cadmium-mercury-telluride, infra-red detector elements for use in a synchronous meteorological satellite (SMS) launched from Cape Canaveral on 15 May 1974.

The satellite's first work will be to watch the life cycle of short-lived storms that could form and die without ever being observed by satellites in a lower-altitude polar orbit.

The Visible Infra-red Spin-scan Radiometer (VISSR) provides day-time images of nearly one quarter of the earth's surface in 18 minutes. Pictures show such fine detail because each image contains 14 600 transmission lines compared with the normal 625-lines from standard United Kingdom television pictures.

Maps of wind direction and force for several levels in the atmosphere are made from time-lapse cloud motion measurements using the infra-red channels. The height of the observed wind velocity is deduced from the measurement of cloud-top temperature. This technique has proved useful during the GATE experiment.

The detectors were produced by Mullard at Southampton. Because of the extreme sensitivity of the detectors to minute changes in temperature, 'heat maps' of the earth's surface are taken by the SMS and transmitted back to earth to provide scientists with valuable meteorological and geological data. The detectors are most sensitive when they are cooled to low temperatures. This is achieved by a radiation cooler which allows any heat generated within the detector to leak into space. By use of this technique, temperatures lower than 100 kelvins (-173°C) are made possible.

Laser radar installation at Beaufort Park

The large laser radar installation at Beaufort Park has been brought into operation and observations of Raman scattering from the stratosphere have been obtained. The results are encouraging as the number densities of air molecules calculated from the scattering data agree with those calculated from radiosonde observations in the region where the two methods of measurement overlap.

Building Climatology Section set up

A Building Climatology Section consisting of one Principal Scientific Officer and one Scientific Officer and funded by the Department of the Environment (DOE) has been set up in the Climatological Services Branch to work on projects specified by DOE.

Pressure data for the British Gas Corporation

A twice daily service of actual and forecast atmospheric pressure values has been supplied to the British Gas Corporation Liquid Natural Gas sites at Glen Mavis, Airdrie, since 27 February 1974 and Partington, Manchester, since 1 March 1974.

Contract for data buoy

The Department of Trade and Industry has placed a contract for the development and construction of the first United Kingdom national data buoy, DB-1. The Office is acting as design authority for the meteorological subsystem.

Analyses of WAMFLEX project

Analysis of data from the WAMFLEX project has now been completed; the object of the project was to measure the vertical transfer of horizontal momentum over large mountains (in this case the Rockies). Wind and temperature data secured by the Canberra when flying at a common flight level with other aircraft show perfect agreement with data from those aircraft, and flux profiles obtained from three aircraft flying in a 'stack' look reasonable. Significant transfers of momentum flux ($0.3\text{--}0.5\text{ N/m}^2$ at most levels) occurred on three days.

Transfer of radiation work

The transfer of all non-routine work on solar radiation and instrumentation from Kew Observatory to Beaufort Park was completed in January 1974.

Computerized radiosonde equipments

Contracts were placed with Ferranti, Wythenshawe, in March for the computerized station ground equipments and automated central calibration plant for the Mk 3 radiosonde system. The first ground station will be tested at Beaufort Park during the second half of 1975 while the central calibration plant will be brought into operation at Eastern Road during the same period.

Pollution sampling over the North Sea

In the Meteorological Office's study of the long-range transport of industrial pollution, a further series of sampling flights was carried out by Meteorological Research Flight in dry westerlies during August and September 1973. These included measurements of sulphate particles as well as sulphur dioxide gas. The analysis of the data, which has now been completed, leads to new estimates of approximately one-third for the fraction of sulphur pollution deposited on the ground before the air crossed the east coast. In the remainder of the programme the opportunity was taken of making similar measurements off the Danish and Norwegian coasts, with the aim of obtaining information on the further loss by deposition over the sea.

Computer Output Microfilm in the production of the *Monthly Weather Report*

Commencing with the January 1974 issue, printer's copy of the tabular material of the *Monthly Weather Report* has been in the form of Calcomp film. This new system will eliminate manual type-setting and proof reading. Calcomp-plotted charts are also being used in the production of the maps of mean air temperature, mean daily sunshine and 30-cm earth temperature anomaly maps although the isopleths are still drawn by hand.

Study of climatic variation

A study of climatic variation over the last few hundred years has revealed the inadequacies of inferring meteorological data from other associated data. For example a comparison of the temperature indications from the ^{18}O content of a Greenland ice core and from the dates of wine harvests in northern France with the central England series have indicated a rather low correlation. It seems unlikely that reliable decadal means for the time before instrumental temperature data can be derived from either of these sources.

The observed meteorological data indicate that over the last 250 years winter temperatures have increased slightly, but large fluctuations have occurred about the trend line.

CORRECTION

Meteorological Magazine, September 1974, p. 266, Table II. For 'Wokingham U.D.' read 'Woking U.D.'.

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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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DAILY SYNOPTIC WEATHER MAPS FROM THE 1780s: A RESEARCH PROJECT OF SYNOPTIC CLIMATOLOGY

By J. A. KINGTON

(Climatic Research Unit, School of Environmental Sciences, University of East Anglia)

Summary. The preparation of a series of daily synoptic weather maps for a number of years in the 1780s is described. The practicability of producing such charts is demonstrated by a discussion of the various sources of meteorological data which are available for this period. Illustrative examples are given of the weather maps being produced. Reference is finally given to methods by which these charts may be applied to improve our understanding of the climatic record over the past 200 years.

Introduction. The synoptic climatological research discussed in this paper is being sponsored by the Meteorological Office for the Meteorological Research Committee. The project was established in the Department of Geography, University College of Swansea in 1967 with the primary object of preparing a series of daily synoptic weather maps for a number of years in the 1780s, covering the area of the British Isles, western Europe and the eastern North Atlantic. In 1971 the working base of the project was transferred to the Climatic Research Unit in the School of Environmental Sciences, University of East Anglia. In assembling all known data for this period and area, over 80 inquiries were directed to scientists working in the fields of historical and synoptic climatology, meteorological services, universities, archives, libraries, scientific academies, learned societies and museums in the British Isles, Europe and the U.S.A. The response to this inquiry has been most rewarding, with the collected data providing a workable synoptic coverage over the specified area on a daily basis for an initial period of four years from 1781. Several research visits have also been made to collect data from archives in England and on the Continent. Preliminary inquiries at the sources of information have indicated that similar data are available for many years onwards from 1786.

Historical background. The search for ordered and rational explanations of natural phenomena was a characteristic feature of scientific inquiry during the eighteenth century. In meteorology, the long-held Aristotelian concepts of atmospheric phenomena were being questioned; concerted efforts, based on scientific observations, began to be made to understand the clearly apparent

fluctuations in the rhythm of the seasons which critically controlled the success or failure of the agricultural economies of most European states. Also the ancient hypothesis which suggested that epidemics were influenced by weather conditions began to be systematically investigated for the first time.

Eighteenth century scientific societies and meteorological observations. There were several attempts to organize meteorological observations on a systematic and collective basis during the eighteenth century. In 1723 a scheme for the collection of standardized weather reports was organized by James Jurin (1684–1750) under the auspices of the Royal Society and, for a time, observations were received from several locations in England, Europe, North America and India. In 1776 the Société Royale de Médecine (S.R.M.) was founded in France under the patronage of Louis XVI with Louis Cotte (1740–1815) as its scientific adviser. The objectives and achievements of this society have been discussed elsewhere (Kington¹). A similar society, the first one to be specifically devoted to meteorology, the Societas Meteorologica Palatina (S.M.P.) was founded at Mannheim under the patronage of the Elector Karl Theodor with J. J. Hemmer (1733–90) as its director. The contribution of this society to the development of meteorological observing during the latter part of the eighteenth century has been discussed elsewhere (Kington²).

The activities of other scientific societies in northern Europe in establishing meteorological and astronomical observatories in Denmark, Norway, Sweden, the Faeroes, Greenland and Iceland (see Figure 1) have also been described elsewhere (Kington³). Most of the stations of these various networks were equipped with standard sets of instruments including a barometer, thermometers, hygrometer, rain-gauge and wind vane. The high-quality craftsmanship of instrument-makers during the eighteenth century allowed the design and construction of meteorological instruments to become quite sophisticated. Besides instrumental readings, observers were instructed to record significant weather, state of sky, clouds and wind strength; standardized abbreviations and symbols were used in the registers. Observations were usually made thrice-daily at the standard times of 07 h, 14 h and 21 h, and for the S.R.M. and S.M.P. networks, were entered on specially prepared forms which were periodically sent to the headquarters at Paris and Mannheim for analysis and interpretation (see Figures 2 and 3). Astronomical and phenological observations were also made by many of the observers. In England comparable efforts were made on a more individual basis by a dedicated group of amateurs mostly drawn from the medical and clerical professions. Observational procedures and findings were often compared, with the Royal Society providing a formal centre for the discussion and exchange of ideas. The efforts of Jurin to establish a network of observing stations under the auspices of the Royal Society earlier in the century had probably not been forgotten and reasonably standardized observations were being made on a daily basis at several locations in England during the 1780s. The usefulness of ships' log-books in providing meteorological data about conditions over the sea and in coastal regions off western Europe during this period has been discussed elsewhere (Oliver and Kington⁴). There are large collections of log-books from Royal Navy ships from about 1670 onwards at the National Maritime Museum and at the Public Record Office (see Figure 4). Log-books of vessels of the old East India Company are available at the India Office Records, Foreign and Commonwealth Office, London.

The image shows two pages of a handwritten register. The left page is headed 'Afterskole-Register' and the right page is headed 'Afterskole-Register'. Both pages have columns for 'Tid' (Time), 'Barometer' (Paris inches, lines, quarters or sixths), 'Thermometer' (degrees Réaumur), 'Wind' (direction and strength), and 'Sky' (state of sky and significant weather). The entries are dated May 1782 and are kept at Lambhús (Iceland) by Rasmús Lievog. The handwriting is in a cursive script, likely Danish or Icelandic, with some English words interspersed.

FIGURE 1—REGISTER OF OBSERVATIONS FOR MAY 1782 KEPT AT LAMBHÚS (ICELAND) BY RASMÚS LIEVOG

The two pages illustrated are of observations made in the morning (0600) and at midday (1200). The columns contain readings of barometer (Paris inches, lines, quarters or sixths); exterior thermometer (degrees Réaumur); wind direction; state of sky and significant weather. This last column also contains standard terms used by Danish observers to describe wind strength. (From Kingston.)*

Units. At stations in the British Isles, pressure was recorded in English inches and temperature in degrees Fahrenheit. On the Continent pressure was usually recorded in Paris inches and lines,* and temperature in degrees Réaumur, although there were a few exceptions, for example: Basel (pressure in millimetres and temperature in degrees Celsius); Stockholm (pressure in Swedish decimal inches and temperature in degrees Celsius up to December 1782); and Vienna where pressure was recorded in Viennese inches and temperature in degrees Celsius.

The approach of synoptic meteorology. Although a large number of weather observations were made and collected during the latter part of the eighteenth century, particularly from about 1780 onwards, the key factors for their meteorological analysis and interpretation had yet to be realized. It was only in the 1820s that H. W. Brandes (1777–1834), using data collected over Europe in the 1780s, constructed a series of daily weather maps which showed that the surface wind field was clearly related to the pressure pattern and that centres of low pressure tended to move from west to east. Unfortunately for the advancement of synoptic meteorology, the original charts that Brandes constructed do not appear to have been preserved, although a sample

* 12 Paris inches = 144 Paris lines = 32.48 cm; 332.5 Paris lines = 1000.0 mb.

- (a) Daily synoptic weather maps from 1 January 1781 for as many years as the project continues, covering the British Isles, western Europe and the eastern North Atlantic. An illustrative chart sequence is given in Appendix I.

1781 1782

OBSERVATIONES HAFNIENSES (1784)

Autore BUGGE.

Hæcæ observationis ordinariæ 7 mat. 12 merid. 9. vesp.

Januarius.

	Barom.	Therm. intern.	Therm. extern.	Hygr.	Declin.	Ventus.	Pluvia.	Evap.	Mare baltic.	Luna.	Cœli fac.	Meteor.
	ing. lin. dec.	gr. dec.	gr. dec.	gr. dec.	gr. min.	direct.	viros.	poli. cub.	lin. dec.	poli.		
19 1	28, 2, 8	0, 1	-6, 0	31, 4	18, 16				6		☉	
	2, 9	0, 0	-3, 9	31, 0	16				6		☉	
	3, 1	0, 3	-5, 5	31, 3	16	ONO 2			2		☉	
20 2	28, 4, 9	0, 8	-6, 6	31, 7	18, 16	NO 2			-3		☉	
	5, 9	0, 4	-5, 2	31, 6	16	NO 2			-1		☉	
	6, 8	0, 7	-6, 3	31, 5	14	ONO 3			8		☉	
33 3	28, 7, 8	0, 7	-4, 8	31, 3	18, 14	O 3			-4		☉	
	7, 6	0, 5	-4, 1	31, 1	13	O 6 O 3			16		☉	
	9, 0	0, 3	-3, 4	30, 9	15	SO 2			-14		☉	
41 4	28, 9, 8	0, 4	-5, 0	31, 0	18, 15	SSO 2			-18		☉	
	10, 1	0, 3	-3, 9	30, 6	15	SSO 2			-35		☉	
	9, 9	0, 2	-3, 3	30, 4	15	SO 1			-29		☉	
41 5	28, 10, 0	0, 3	-3, 5	30, 3	18, 15	O 5 O 2			-9		☉	
	10, 0	0, 2	-1, 7	30, 1	15	O 1			-22		☉	
	10, 3	0, 2	-1, 5	29, 4	15	O 1			-11		☉	
43 6	28, 10, 5	0, 2	-2, 8	29, 3	18, 15	O 1			-7		☉	
	10, 8	0, 1	-0, 9	29, 2	15	O 1			-7		☉	
	10, 7	0, 2	-3, 0	29, 0	15	O 1			-9		☉	
31 7	28, 9, 9	0, 3	-5, 0	29, 2	18, 15	SO 1			-4	☾ h. 2m. 43	☉	
	9, 5	0, 3	-3, 1	29, 2	15	SO 2			-8	per.	☉	
	8, 7	0, 3	-4, 2	29, 3	16	SO 2			-14		☉	
32 8	28, 7, 5	0, 3	-5, 8	29, 3	18, 16	SO 1			-10		☉	
	7, 2	0, 2	-2, 3	29, 3	17	SSO 2			-6		☉	
	5, 9	0, 2	-2, 7	29, 2	16	SSO 2			-16		☉	
27 9	28, 5, 6	0, 1	-2, 7	29, 1	18, 16	SO 2			-15		☉	
	5, 6	0, 1	-2, 2	29, 0	16	SO 2			-14		☉	
	6, 6	0, 2	-3, 5	28, 8	16	SSO 2			-12		☉	
33 10	28, 7, 0	0, 3	-6, 0	28, 8	18, 16	SW 2			-10		☉	
	7, 4	0, 3	-5, 6	28, 8	16	SW 2			-4		☉	
	6, 6	0, 5	-8, 0	29, 3	16	W S W 2			-5		☉	
23 11	28, 4, 9	0, 6	-6, 8	29, 3	18, 16	W 2			-12		☉	
	4, 1	0, 5	-2, 0	28, 8	16	W S W 2			-4		☉	
	2, 7	0, 0	1, 5	27, 8	16	W 2			-6		☉	
17 12	28, 2, 3	0, 2	1, 5	25, 9	18, 16	WNW 2			-4		☉	
	2, 3	0, 4	2, 1	25, 6	16	WNW 2			-3		☉	
	2, 8	0, 5	1, 4	25, 2	15	WNW 1			-5		☉	
16 13	28, 2, 2	0, 5	1, 7	25, 4	18, 15	W 2			-4		☉	
	1, 8	0, 7	1, 6	24, 9	14	W 2			-2		☉	
	1, 1	0, 8	2, 5	25, 3	14	W 2			-2		☉	
13 14	28, 0, 7	0, 9	2, 0	25, 0	18, 16	W 2			-4		☉	
	0, 7	1, 1	1, 3	24, 6	19	W 2	28		-2		☉	
	2, 10, 9	1, 3	2, 5	24, 5	18	W S W 2			-3		☉	
00 15	27, 9, 7	1, 3	2, 5	24, 5	18, 24	W S W 2			-4	☾ h. 5 m. 25	☉	
	8, 5	1, 4	2, 8	24, 5	29	W 2			-8	vesp.	☉	
	4, 2	1, 3	0, 9	24, 5	27	NW 2			-12		☉	

☉ h. 2m. 43 per.

☉ h. 5 m. 25 vesp.

☉ h. 2m. 43 vesp.

FIGURE 3—EXTRACT FROM THE EPHEMERIDES OF THE SOCIETAS METEOROLOGICA PALATINA, SHOWING OBSERVATIONS MADE BY PROFESSOR THOMAS BUGGE AT COPENHAGEN FROM 1 TO 15 JANUARY 1784

The columns contain thrice-daily readings (0700, 1200 and 2100) of barometer (Paris inches, lines and tenths); interior and exterior thermometers (degrees Réaumur); hygrometer; magnetic declination; wind velocity; height of Baltic; state of sky and significant weather. Rainfall and phases of the moon were also regularly recorded. (From Kingston.²)

- (b) Monthly weather reviews giving the general synoptic situation for the entire area covered by the plotted data; wind, weather and temperature over selected area(s) of the chart (for example, central and southern England) and noteworthy events of meteorological and general significance that had occurred anywhere on the charts. A sample review for November 1784 is given in Appendix II.
- (c) A classification of the daily weather types over the British Isles comparable to that contained in Lamb's register from 1861. Results obtained from the series of charts already completed are given in Table I.

1783 Dec 27 Sat		Drizzle & light rain S. Wind		1784 Jan 1 Thurs		Drizzle & light rain S. Wind	
1783 Dec 28 Sun		Drizzle & light rain S. Wind		1784 Jan 2 Fri		Drizzle & light rain S. Wind	
1783 Dec 29 Mon		Drizzle & light rain S. Wind		1784 Jan 3 Sat		Drizzle & light rain S. Wind	
1783 Dec 30 Tue		Drizzle & light rain S. Wind		1784 Jan 4 Sun		Drizzle & light rain S. Wind	
1783 Dec 31 Wed		Drizzle & light rain S. Wind		1784 Jan 5 Mon		Drizzle & light rain S. Wind	
1784 Jan 1 Tue		Drizzle & light rain S. Wind		1784 Jan 6 Tue		Drizzle & light rain S. Wind	
1784 Jan 2 Wed		Drizzle & light rain S. Wind		1784 Jan 7 Wed		Drizzle & light rain S. Wind	
1784 Jan 3 Thu		Drizzle & light rain S. Wind		1784 Jan 8 Thu		Drizzle & light rain S. Wind	
1784 Jan 4 Fri		Drizzle & light rain S. Wind		1784 Jan 9 Fri		Drizzle & light rain S. Wind	
1784 Jan 5 Sat		Drizzle & light rain S. Wind		1784 Jan 10 Sat		Drizzle & light rain S. Wind	
1784 Jan 6 Sun		Drizzle & light rain S. Wind		1784 Jan 11 Sun		Drizzle & light rain S. Wind	
1784 Jan 7 Mon		Drizzle & light rain S. Wind		1784 Jan 12 Mon		Drizzle & light rain S. Wind	
1784 Jan 8 Tue		Drizzle & light rain S. Wind		1784 Jan 13 Tue		Drizzle & light rain S. Wind	
1784 Jan 9 Wed		Drizzle & light rain S. Wind		1784 Jan 14 Wed		Drizzle & light rain S. Wind	
1784 Jan 10 Thu		Drizzle & light rain S. Wind		1784 Jan 15 Thu		Drizzle & light rain S. Wind	
1784 Jan 11 Fri		Drizzle & light rain S. Wind		1784 Jan 16 Fri		Drizzle & light rain S. Wind	
1784 Jan 12 Sat		Drizzle & light rain S. Wind		1784 Jan 17 Sat		Drizzle & light rain S. Wind	
1784 Jan 13 Sun		Drizzle & light rain S. Wind		1784 Jan 18 Sun		Drizzle & light rain S. Wind	
1784 Jan 14 Mon		Drizzle & light rain S. Wind		1784 Jan 19 Mon		Drizzle & light rain S. Wind	
1784 Jan 15 Tue		Drizzle & light rain S. Wind		1784 Jan 20 Tue		Drizzle & light rain S. Wind	
1784 Jan 16 Wed		Drizzle & light rain S. Wind		1784 Jan 21 Wed		Drizzle & light rain S. Wind	
1784 Jan 17 Thu		Drizzle & light rain S. Wind		1784 Jan 22 Thu		Drizzle & light rain S. Wind	
1784 Jan 18 Fri		Drizzle & light rain S. Wind		1784 Jan 23 Fri		Drizzle & light rain S. Wind	
1784 Jan 19 Sat		Drizzle & light rain S. Wind		1784 Jan 24 Sat		Drizzle & light rain S. Wind	
1784 Jan 20 Sun		Drizzle & light rain S. Wind		1784 Jan 25 Sun		Drizzle & light rain S. Wind	
1784 Jan 21 Mon		Drizzle & light rain S. Wind		1784 Jan 26 Mon		Drizzle & light rain S. Wind	
1784 Jan 22 Tue		Drizzle & light rain S. Wind		1784 Jan 27 Tue		Drizzle & light rain S. Wind	
1784 Jan 23 Wed		Drizzle & light rain S. Wind		1784 Jan 28 Wed		Drizzle & light rain S. Wind	
1784 Jan 24 Thu		Drizzle & light rain S. Wind		1784 Jan 29 Thu		Drizzle & light rain S. Wind	
1784 Jan 25 Fri		Drizzle & light rain S. Wind		1784 Jan 30 Fri		Drizzle & light rain S. Wind	
1784 Jan 26 Sat		Drizzle & light rain S. Wind		1784 Jan 31 Sat		Drizzle & light rain S. Wind	

FIGURE 4—EXTRACT FROM LOG-BOOK OF H. M. CUTTER 'COCKATRICE' FROM SATURDAY 27 DECEMBER 1783 TO THURSDAY 8 JANUARY 1784, WHILST CRUISING OFF THE COAST OF SUSSEX

The entry for Thursday 1 January 1784 gives a typical example of the daily weather information that is obtainable from this source:

- First part: ESE fresh gales with snow and rain;
Middle part: Variable fresh breezes and cloudy;
Latter part: N light airs and cloudy.

(From Oliver and Kingston.⁴) Facsimile of Crown copyright record in the Public Record Office (reference ADM 51).

TABLE I—BRITISH ISLES DAILY WEATHER-TYPE FREQUENCIES 1781–84

	W	NW	N	E	S	A	C	U
1781								
January	8	0	2	7	0	8	5	1
February	11	8	2	0	1	3	3	0
March	6	1	2	3	1	18	0	0
April	8	1	1	2	3	9	5	1
May	0	0	1	13	2	10	5	0
June	2	1	0	5	2	3	16	1
July	12	1	0	0	3	11	4	0
August	2	1	1	1	0	5	19	2
September	7	5	4	1	2	6	5	0
October	5	5	4	0	1	15	1	0
November	7	7	1	0	3	4	7	1
December	7	0	0	5	10	1	7	1
Year	75	30	18	37	28	93	77	7
1782								
January	18	3	1	1	1	4	3	0
February	6	0	2	8	1	8	3	0
March	10	1	7	3	1	2	5	2
April	0	1	3	14	1	1	9	1
May	3	0	3	7	1	1	16	0
June	6	3	0	1	3	9	7	1
July	4	5	1	2	2	5	9	3
August	8	5	3	0	1	0	14	0
September	3	0	2	5	5	6	9	0
October	6	6	3	3	1	8	3	1
November	3	0	6	1	3	8	7	2
December	8	5	1	1	3	12	0	1
Year	75	29	32	46	23	64	85	11
1783								
January	10	2	3	1	1	3	11	0
February	9	1	2	1	0	5	10	0
March	4	2	3	3	1	9	7	2
April	5	0	2	5	3	14	0	1
May	7	1	6	5	0	9	3	0
June	5	0	1	1	2	12	8	1
July	8	1	0	2	7	5	7	1
August	4	0	1	1	2	7	13	3
September	9	3	0	1	1	8	6	2
October	6	6	3	3	1	8	3	1
November	2	0	4	2	5	9	8	0
December	1	0	0	4	5	16	4	1
Year	70	16	25	29	28	105	80	12
1784								
January	3	1	7	4	2	8	5	1
February	3	2	8	6	3	5	2	0
March	1	1	4	9	3	8	5	0
April	4	5	5	1	0	7	8	0
May	11	2	2	0	1	13	2	0
June	6	4	3	3	1	2	9	2
July	8	6	1	1	1	11	3	0
August	6	3	4	3	1	11	3	0
September	6	0	1	1	5	10	5	2
October	1	2	2	5	3	16	2	0
November	8	2	3	3	0	6	6	2
December	0	2	7	8	0	9	5	0
Year	57	30	47	44	20	106	55	7

Key to types:

W Westerly
 NW North-westerly
 N Northerly
 E Easterly

S Southerly
 A Anticyclonic
 C Cyclonic
 U Unclassifiable

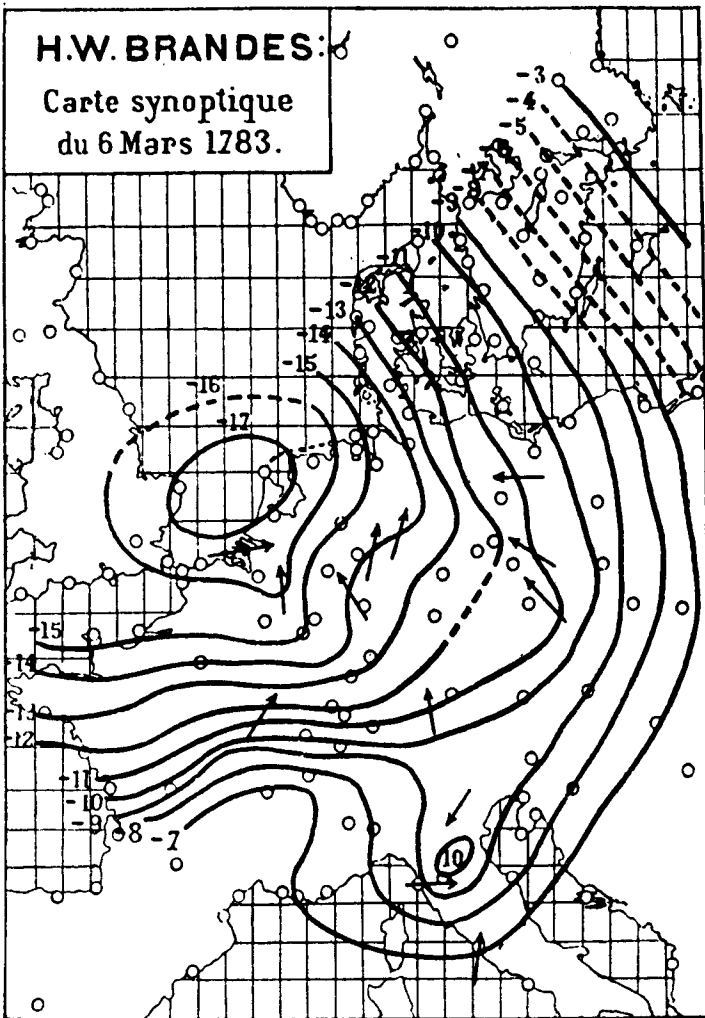


FIGURE 5—SYNOPTIC WEATHER MAP FOR 6 MARCH 1783 BY H. W. BRANDES

This chart was reconstructed from data analysed by H. W. Brandes and shows arrows of surface wind direction and isopleths of equal departure of pressure from normal. (From Ludlam.¹⁰)

Future climatological research which should be possible with the aid of these synoptic weather maps could include:

- (a) Classification and analysis of circulation patterns over the eastern North Atlantic-European sector, as an extension to the investigation already mentioned in (c) above.
- (b) Determination of the most probable upper-air patterns and depression trajectories over the eastern North Atlantic-European sector.

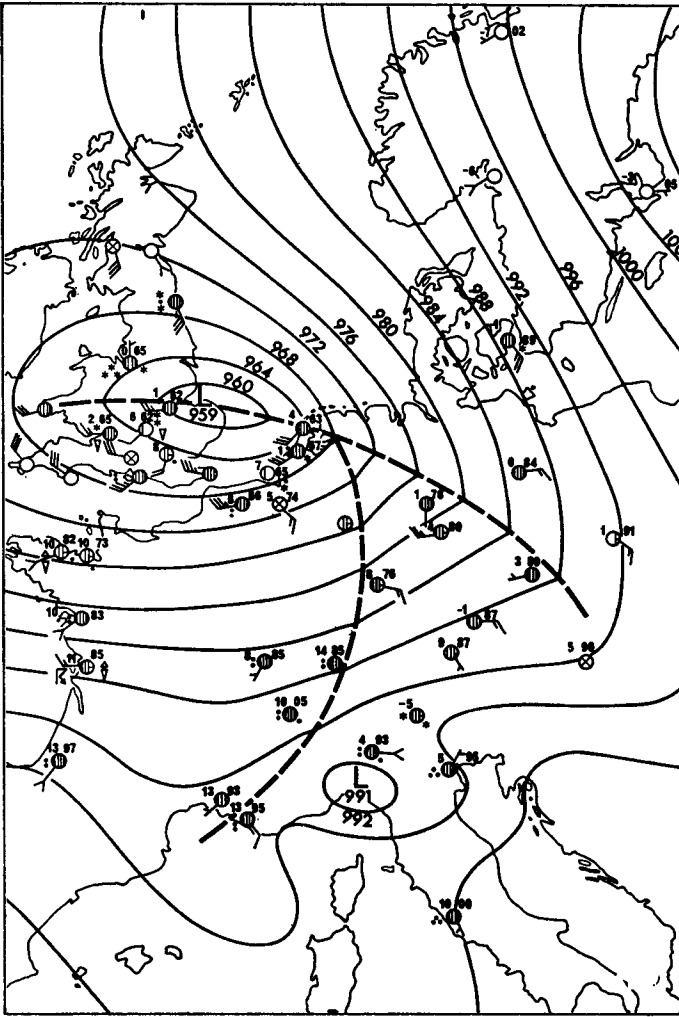


FIGURE 6—SYNOPTIC WEATHER MAP FOR 1400, 6 MARCH 1783 BY J. A. KINGTON

This chart forms part of the present series as discussed in this paper. Pressures are expressed in millibars.

- (c) Analysis of a zonal index measured over the eastern North Atlantic-European sector.
- (d) Analysis of weather singularities during the years studied.
- (e) Application of the methods used by Murray and Lewis⁶ and Murray and Benwell⁷ to analyse weather types using *PSCM* indices.
- (f) Comparison of temperature values associated with the same winds and weather types over selected periods with reference to methods discussed by Perry and Barry.⁸

Conclusion. It is hoped that the results being achieved in this project will provide a synoptic framework within which further climatological research of the type outlined above could be initiated. Data exist for the production of daily weather maps onwards from the years already completed and in the long run as many years as possible from 1781 to 1860 could be similarly treated so as to link up with the existing series of synoptic charts from 1861 to the present day. Research into synoptic climatology could then be extended on a daily basis over the past 200 years.

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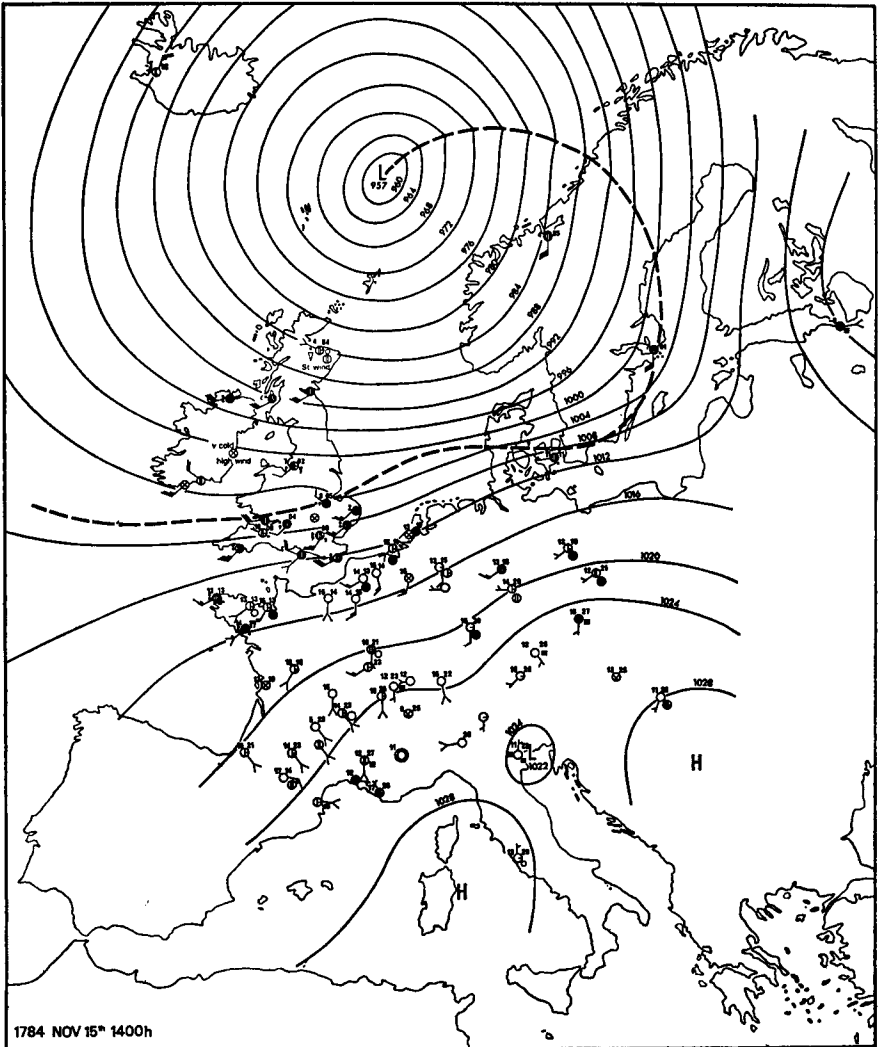
The author is also grateful to Mr D. Mew (Cartographer) and Mr P. Scott (Photographer) of the School of Environmental Sciences and Mr M. Howard of the Audio-Visual Centre, University of East Anglia who prepared the weather maps illustrated in this paper from the original working charts.

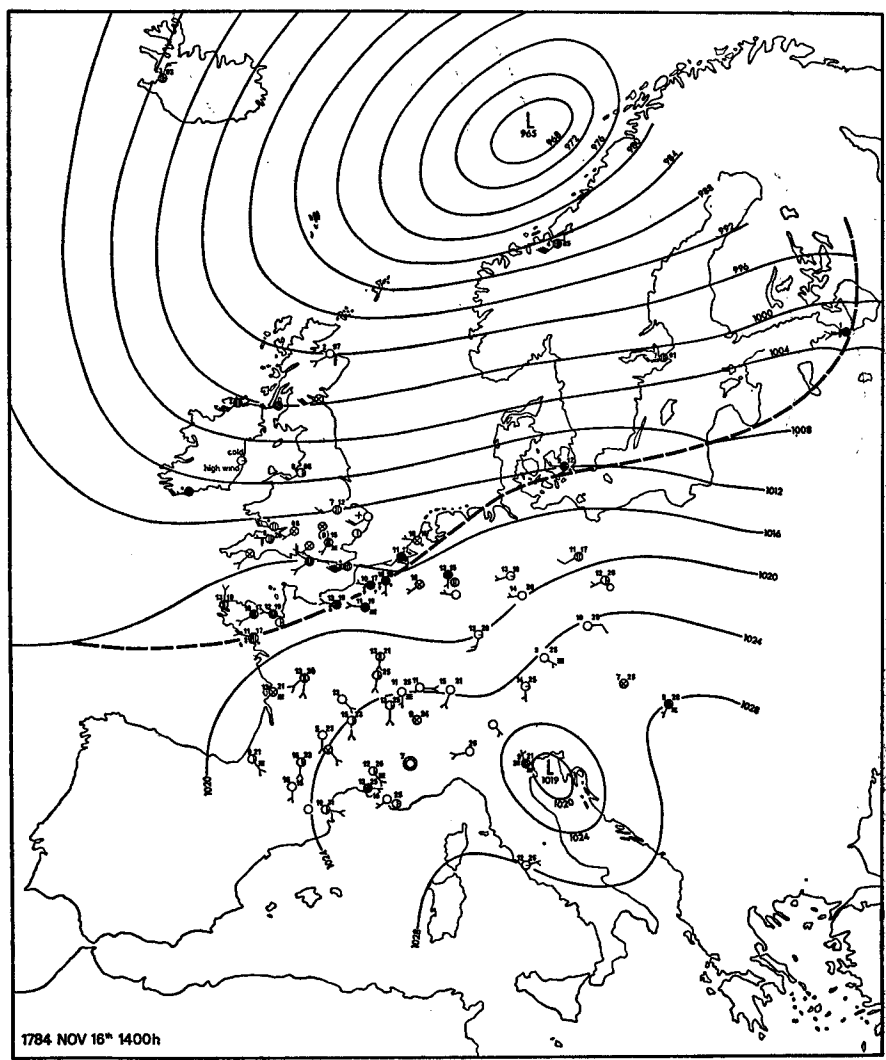
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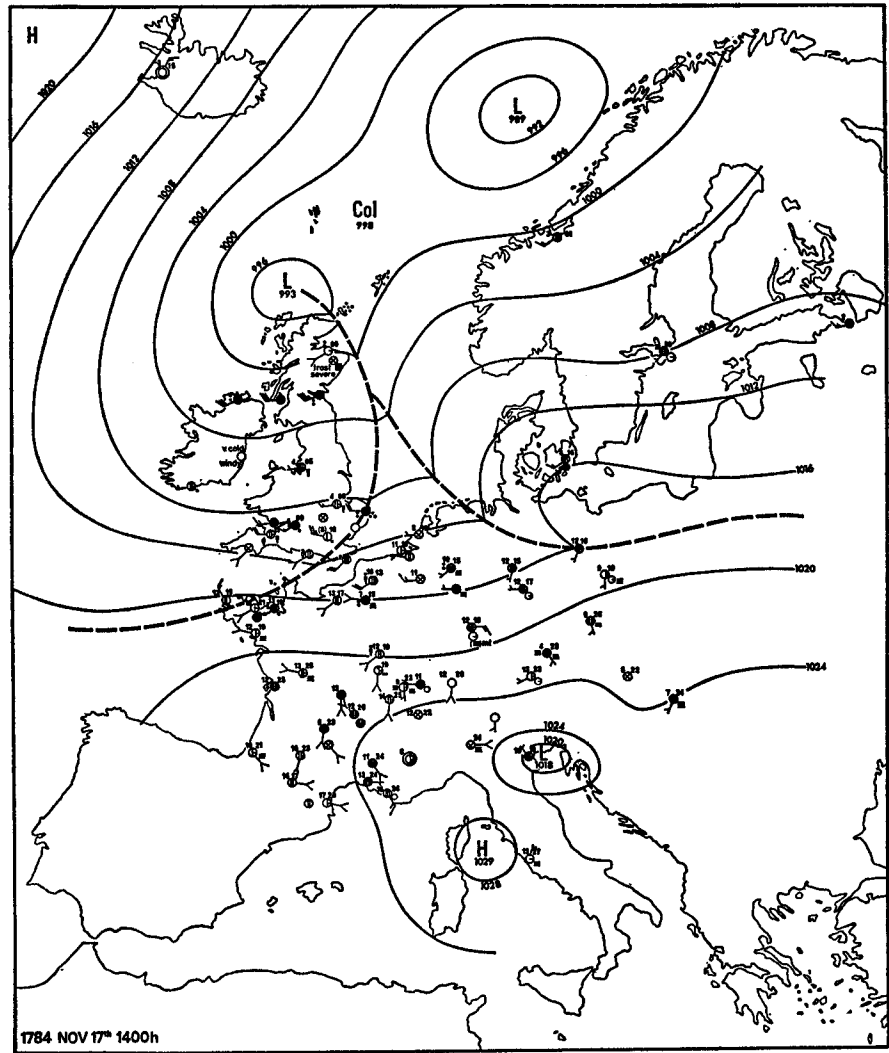
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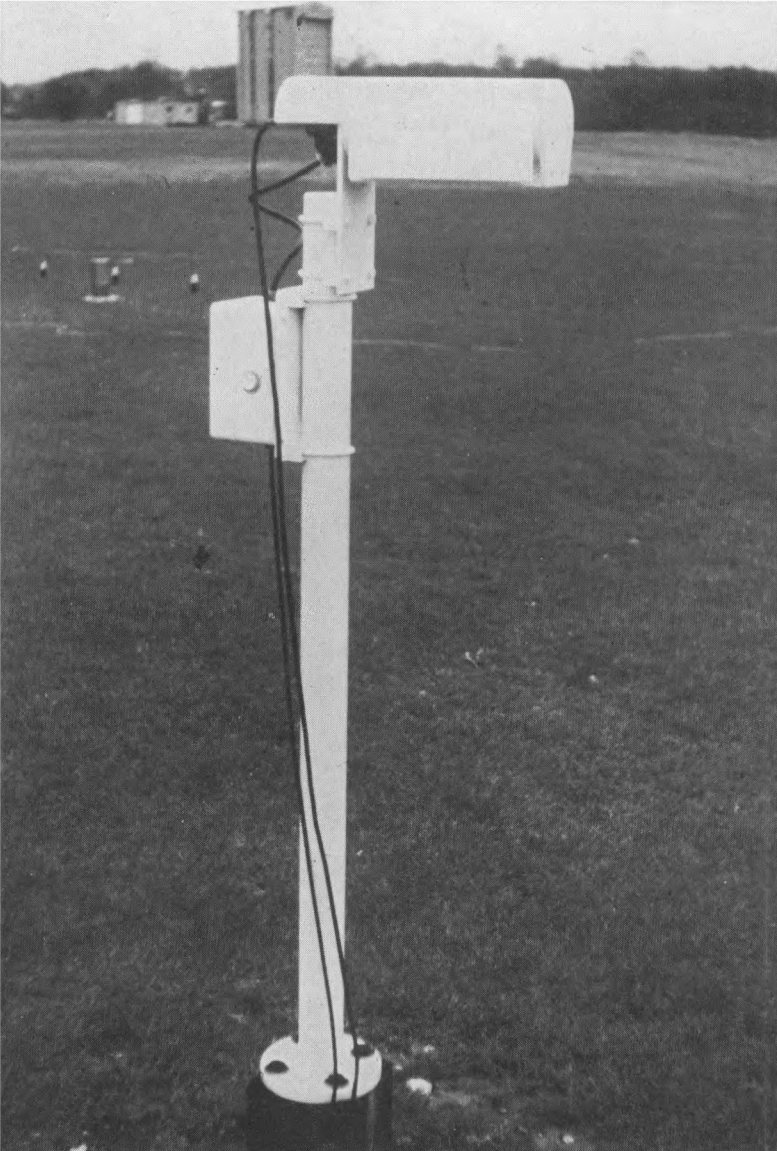
APPENDIX I—ILLUSTRATIVE CHART SEQUENCE FOR
15–21 NOVEMBER 1784

Pressures are expressed in millibars.









**PLATE I—AUTOMATIC WEATHER STATION VERSION OF DEW-CELL SHOWING SIDE
FLAPS ADDED TO ORIGINAL SHIELD**

(See page 53.)

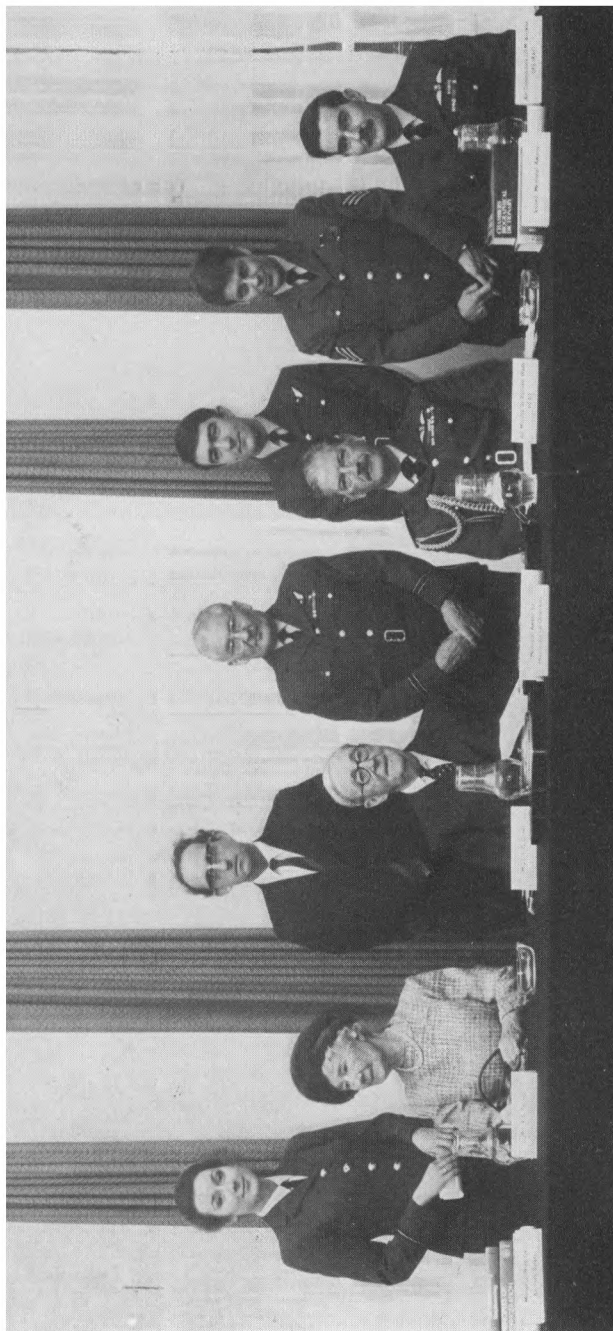


PLATE II—AWARD WINNERS WITH MAJOR AND MRS K. G. GROVES

Left to right: (seated) Mrs K. G. Groves, Major K. G. Groves, Air Marshal Sir Ruthven Wade, Air Commodore D. F. M. Browne; (standing) Flying Officer Trudi Cant, Dr C. J. Readings, Flight Lieutenant F. Robertson, Flight Lieutenant D. R. Gasson, Sergeant M. Dubeay (see page 58.)



PLATE III—MAJOR K. G. GROVES WITH DR C. J. READINGS, WINNER OF THE PRIZE FOR METEOROLOGY
(See page 58.)

To face page 47



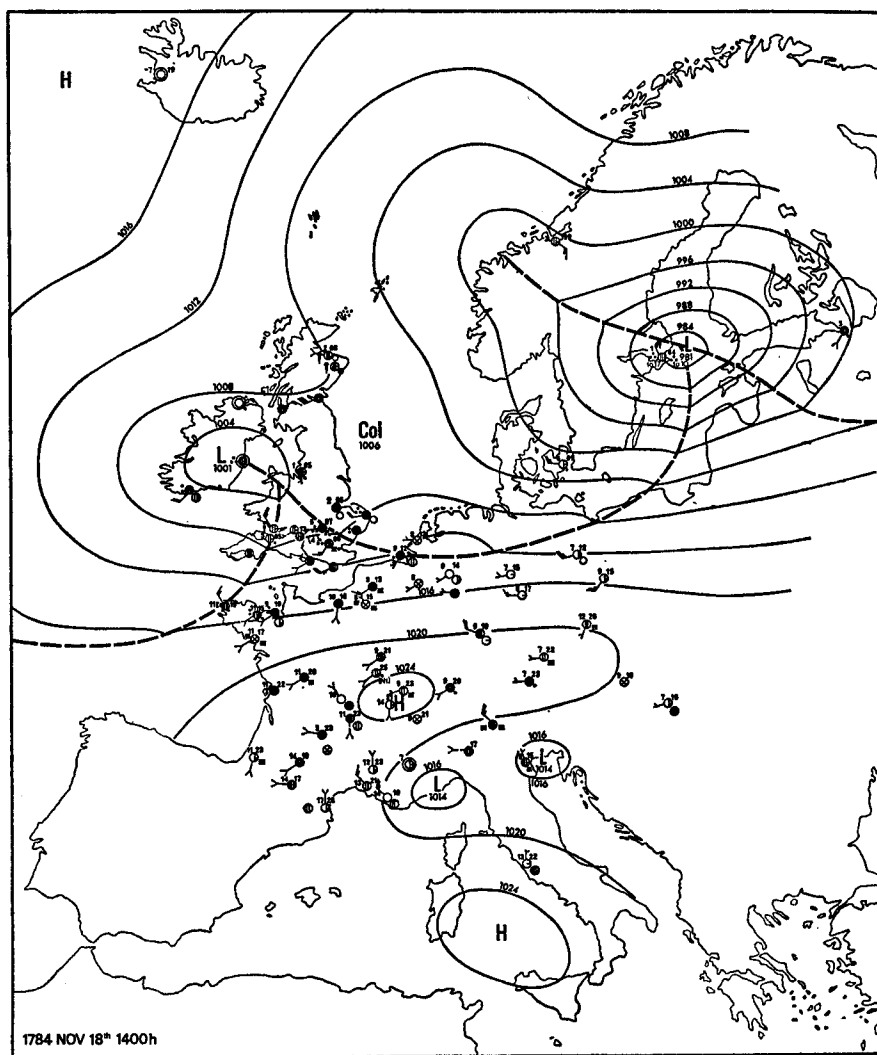
PLATE IV—MAJOR AND MRS K. G. GROVES AT THE PRESENTATION
CEREMONY HELD ON 7 NOVEMBER 1974 ON THE OCCASION OF THEIR
DIAMOND WEDDING ANNIVERSARY

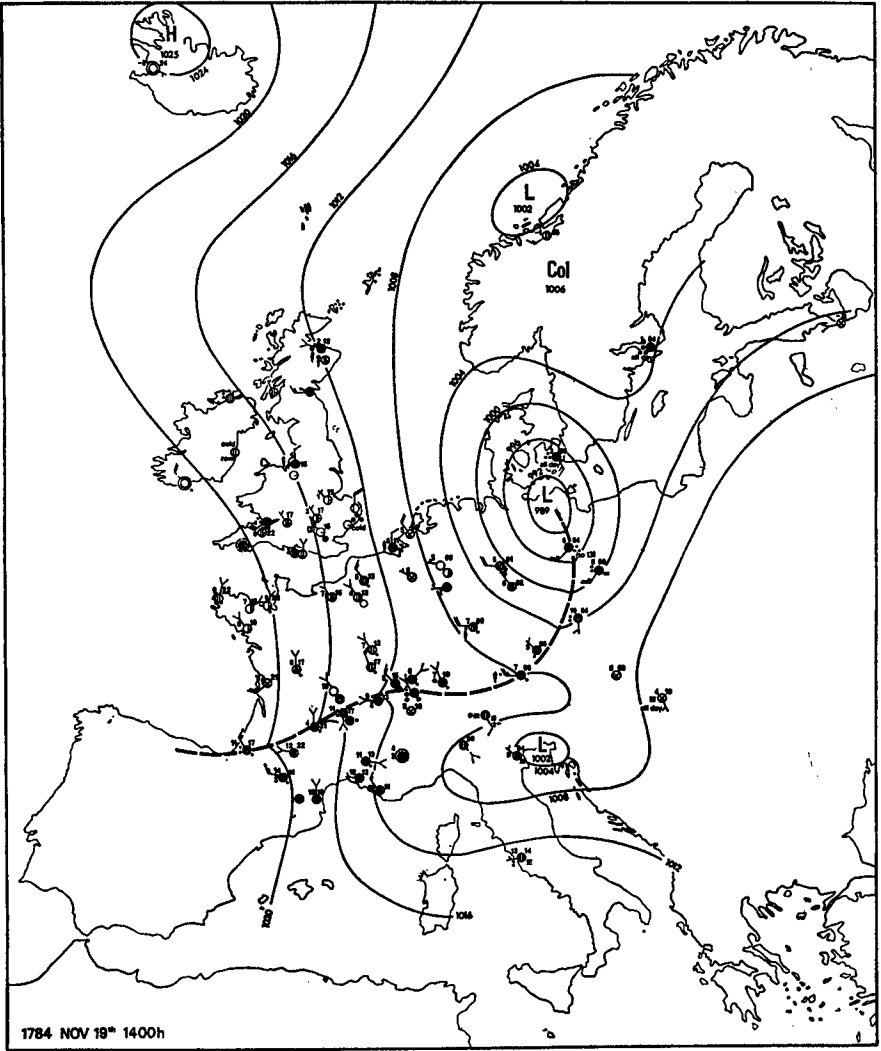
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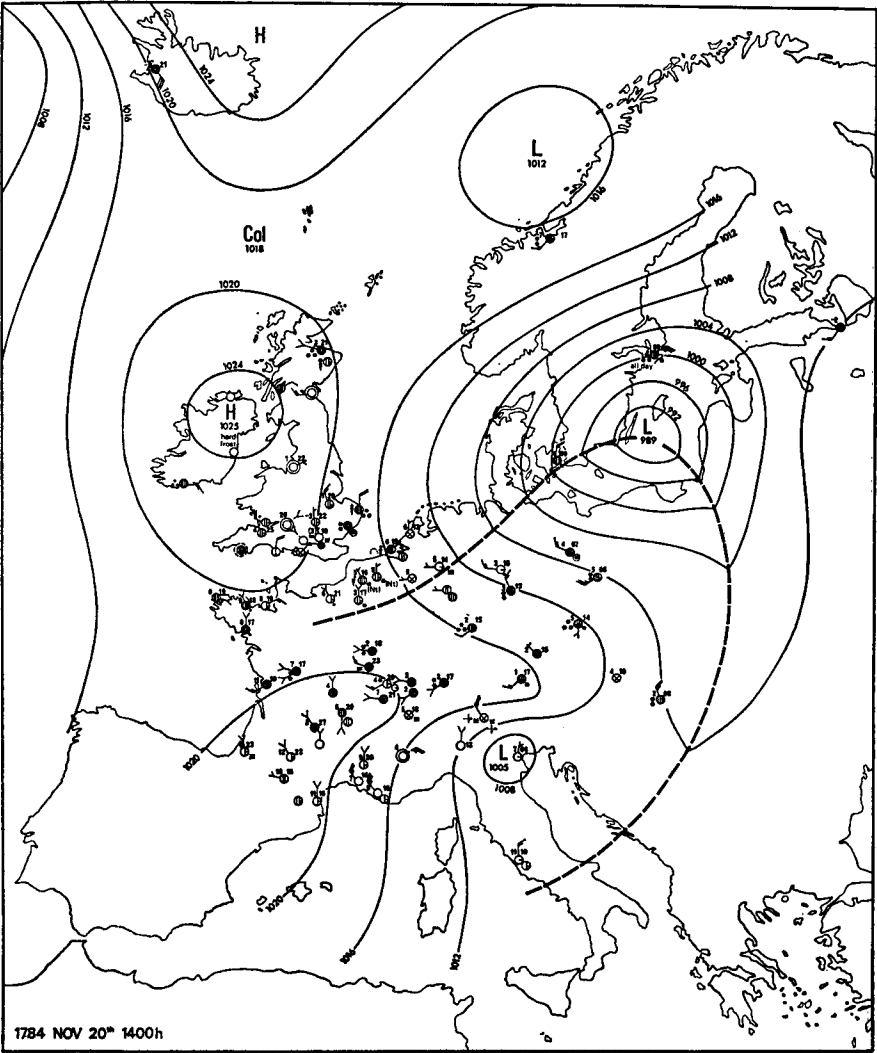


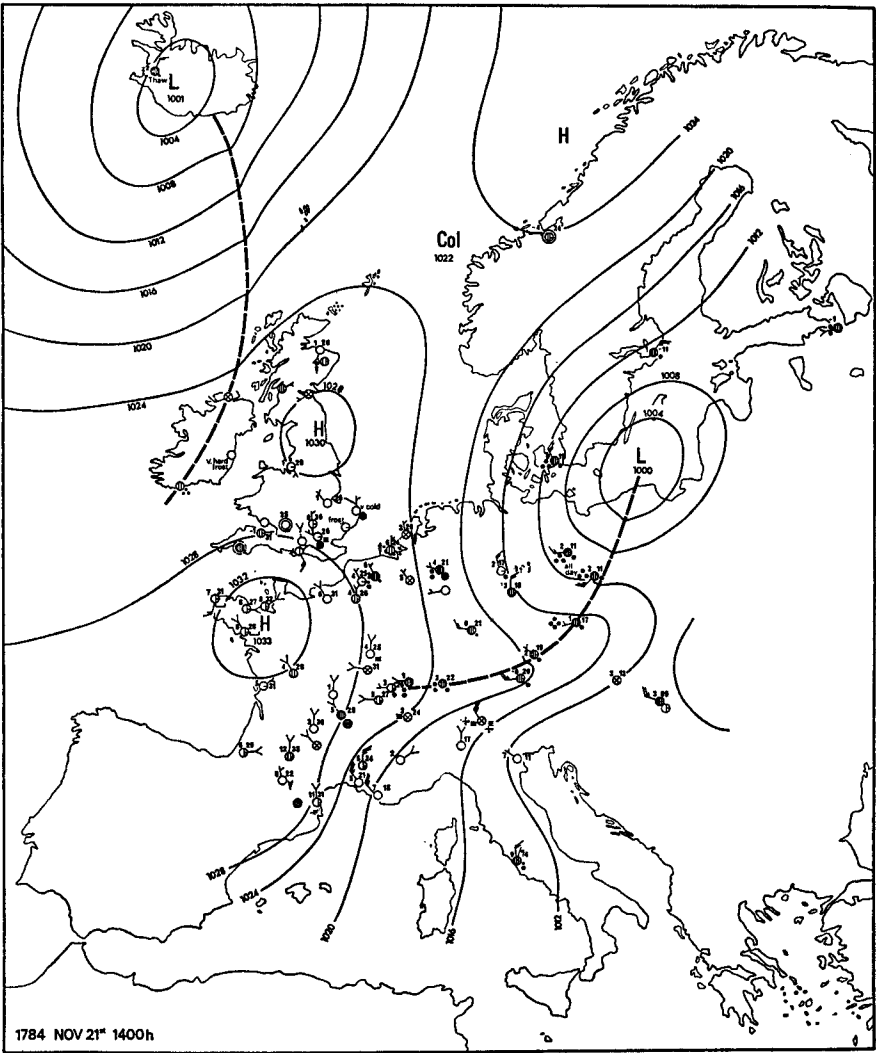
PLATE V—MAJOR K. G. GROVES WITH FLIGHT LIEUTENANT F. ROBERT-
SON, WINNER OF THE AWARD FOR METEOROLOGICAL OBSERVERS

(See page 58.)









APPENDIX II—EXAMPLE OF A MONTHLY WEATHER 'REVIEW NOVEMBER 1784—MOSTLY UNSETTLED AND WET—VERY COLD AT TIMES

In the following descriptions the significance of (a), (b), (c), (d) and (e) is as follows:

- (a) General synoptic situation.
 - (b) Wind
 - (c) Weather
 - (d) Temperature
 - (e) Significant events occurring either within or outside defined areas.
- } over central and southern England.

1st-3rd

- (a) A shallow depression moved east-north-east from the Midlands across the southern North Sea into the southern Baltic as the main centre of low pressure over Iceland moved east into the Norwegian Sea. An anticyclone developed over southern Germany on 2nd to 3rd.
- (b) Light and variable.
- (c) A moist airflow covered much of the Midlands and southern England on 1st giving occasional rain or drizzle. Brighter weather with occasional showers on 2nd and 3rd. Local morning fog patches occurred throughout the period, being particularly persistent in the London area on 1st and 2nd.
- (d) Rather cold to normal.
- (e) 2nd, *Milan*: Date of first snowfall (1784/85).

4th-7th

- (a) An anticyclone over north-west Iceland and another which moved north-north-west from Poland into Scandinavia combined to form a single high-pressure system centred over the Orkneys on 7th. A depression moved east from the south-western Approaches across the Bay of Biscay and central France into north-east Italy.
- (b) Light to moderate, SE backing to NE.
- (c) Occasional rain or drizzle, especially on 5th, and local fog patches. Brighter weather with occasional wintry showers on 7th.
- (d) Rather cold.
- (e) 4th, *Selborne*: 'Great meteor' reported.

8th

- (a) An anticyclone over Scotland on 7th moved quickly south-west to allow a disturbed W'y flow to become established over the Norwegian Sea.
- (b) Light and variable.
- (c) Local morning fog patches, otherwise mainly dry with sunny periods.
- (d) Very cold in inland districts.
- (e) *Berlin*: Date of first snowfall (1784/85).

9th-18th

- (a) A spell of cyclonic conditions: depressions over south-west Iceland, north-east England and Scandinavia deepened and appear to have become grouped together to form a large and complex area of low pressure with the main centre at first over northern Britain on 10th and then over Scandinavia on 12th. A further intense depression moved into the sea area between north-west Scotland and southern Iceland on 14th, and was centred about 200 miles east-north-east of the Faeroes on 15th with a strong W'y flow over the British Isles. During 16th to 17th the depression filled and moved slowly north-east over the Norwegian Sea. On 17th to 18th two succeeding depressions moved east on increasingly southerly tracks from the eastern North Atlantic; the first skirted northern coasts whilst the second passed over Ireland and northern England.
- (b) Moderate to fresh, occasionally strong, mostly SW, becoming cyclonic on 18th.
- (c) Very changeable: occasional rain/drizzle or showers, continuous and moderate to heavy at times, some brief bright intervals.
- (d) Variable: ranging from cold to normal; becoming mild in south on 11th, 14th and 15th.
- (e) 15th, *Europe*: Aurora Borealis observed over a wide area of Europe on the evening and night of the 15th, with reports ranging from Iceland to northern Italy.

19th-21st

- (a) High pressure over Iceland moved steadily east across the Norwegian Sea. An associated anticyclone over Northern Ireland on 20th moved east into northern England on 21st. A further anticyclone was centred over north-west France on 21st. A depression over northern Germany on 19th moved slowly north-east into the Baltic and filled. Cold air spread south over the British Isles and western Europe; particularly low temperatures were recorded over England at midday on 20th and 21st, e.g. -3°C at Mongewell, Oxon on 20th and -2°C in London on 21st.

- (b) Light to moderate NW-NNW, becoming light and variable from the west on 20th-21st.
- (c) Occasional wintry showers decreasing to become generally dry and sunny on 21st, apart from local fog or haze in London area.
- (d) Very cold.

22nd

- (a) With a depression over the Orkneys a weak front was located over England from the Wash to the south-western districts. A sharp ridge extended north-north-east into southern Norway from an anticyclone over south-western France; high pressure was also located over the Icelandic region. A strong N'ly flow occurred over southern Sweden and eastern Germany and gave widespread and continuous snow.
- (b) Light and variable.
- (c) Occasional rain or drizzle and fog patches early and late.
- (d) Very cold.

23rd

- (a) Depressions were located off south-west Iceland and over the Skaggerak. A ridge of high pressure extended northwards over the British Isles from an anticyclone over southern France.
- (b) Light, NNW in east backing to WSW in west.
- (c) Occasional drizzle and fog patches, some local bright intervals.
- (d) Generally cold, but rising to normal in clearer conditions.

24th-27th

- (a) With low pressure over the Icelandic region, a broad WSW'ly flow covered the eastern North Atlantic and most of the British Isles.
- (b) Moderate, WSW backing to S on 27th.
- (c) Occasional rain/drizzle becoming mainly dry from 25th. Local fog patches throughout.
- (d) Normal.

28th-30th. A period of very changeable conditions.

28th

- (a) An intense depression over the Norwegian Sea with a pronounced cold front moving eastwards across all districts of the British Isles.
- (b) Moderate/fresh S veering to NW.
- (c) A wide belt of continuous moderate to heavy rain over western districts moved east to affect central and eastern districts later in day.
- (d) Normal becoming very cold.

29th

- (a) Anticyclones located over Ireland and central Europe. The previous depression had filled and moved east-south-east into the Baltic with a wave developing on the trailing cold front over northern France.
- (b) Moderate to fresh, NNE/NE.
- (c) Continuous rain/drizzle over south-eastern districts becoming dry towards the north-west.
- (d) Very cold to cold.
- (e) (i) *Mulhausen*: Earthquake reported at 2200 h.
(ii) *St Diez*: Earthquake reported at 2130 h.

30th

- (a) A similar situation to that of the 28th with a deep depression off the Norwegian coast and a frontal trough moving south-east over England and Wales.
- (b) Light and variable becoming moderate NW.
- (c) Occasional drizzle and fog patches at first with continuous moderate to heavy rain in the evening.
- (d) Very cold.

551.508.71

THE USE OF THE LITHIUM CHLORIDE HYGROMETER (DEW-CELL) TO MEASURE DEW-POINT

By G. K. FOLLAND

Summary. Trials of a remote-indicating automatic hygrometer which directly measures dew-point are described. The hygrometer can operate without attention for long periods and is particularly suitable as a replacement for wet bulbs in freezing conditions when manual attention to the wet-bulb wick is impossible.

Introduction. A humidity-indicating instrument is required which can operate without attention at automatic weather stations or remote sites where manual attention to wet bulbs in freezing conditions is impossible. A similar instrument is required at synoptic stations where the instrument enclosure is far from the observing office, and remote-indicating instruments which can operate continuously are therefore required. A preliminary investigation of the lithium chloride (dew-cell) hygrometer by MacDowall¹ in 1956 gave promising results, and further trials were carried out by Sparks² in the late 1960s. The present paper describes the results of an intensive investigation of dew-cell performance in which use was made of a modified commercial sensor (Foxboro Type 2701 G24).

Principle of operation. Figure 1 shows the construction of the dew-cell. A 5 per cent solution of lithium chloride is applied to the woven glass-fibre tape which is wound on to a hollow lacquered brass tube. The solution is hygroscopic and absorbs water vapour from the atmosphere. It is also an electrical conductor. The solution is heated resistively by 24-carat gold bifilar windings to which a 25-volt a.c. supply is applied. The temperature of the solution rises at first but the heating effect is reduced when the solution starts to evaporate, since the crystals are poor conductors. An equilibrium is reached when the heat gained by resistive heating equals the heat lost to the environment. The equilibrium temperature depends on the ambient water-vapour pressure, increasing with vapour pressure, and is measured with a close-fitting platinum-resistance thermometer inserted in the hollow brass tube with its bulb half-way along the length of the tube. Plate I shows a typical dew-cell installation. The element is mounted at a height of 1.25 m and is protected from wind, rain and solar radiation by a double-walled, white-painted plastic shield with holes in the base and sides to allow circulation of air. As the dew-cell operates at a high temperature (e.g. about 48°C for a dew-point of 10°C) exchange of air is aided by convection. In series with the heating element is placed a 30-watt lamp whose increasing resistance with increasing current limits the maximum current to the dew-cell.

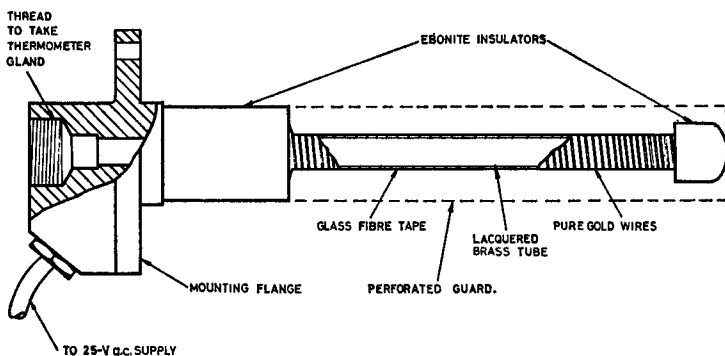


FIGURE 1—DEW-CELL CONSTRUCTION

Operating temperature of the dew-cell. The relationship between the temperature of the dew-cell and the dew-point has been investigated in the laboratory with a device which produces air of known dew-point with an estimated accuracy of about ± 0.1 degC.³ Published data on the saturated vapour pressure of lithium chloride solution are not very reliable, but the equilibrium temperature also depends on the way in which heat is lost to the environment, and thus on the details of the construction of the dew-cell and its housing. It is found that different elements of the same type show a standard deviation of about 0.2 degC in their equilibrium temperature for the same dew-point. Thus a common calibration curve can be used in association with small residual corrections. In practice the temperature-measuring circuitry is arranged so that dew-point, rather than dew-cell temperature, is indicated directly.

Performance of the dew-cell in the field. The dew-cell has been compared with recording aspirated psychrometers⁴ at Kew, Eskdalemuir and Lerwick Observatories and with naturally ventilated wet-bulb and dry-bulb thermometers at two synoptic stations, Little Rissington (Gloucestershire) and Brize Norton (Oxfordshire). At the observatories, chart recorders were used which gave observations at intervals of one minute or less, so that details of short-term fluctuations of dew-point could be investigated. It was found that when the period of fluctuation was a few minutes, the fluctuations recorded by the dew-cell tended to be exaggerated compared with those recorded by the aspirated psychrometers. This effect is due to the nature of the adjustment process of the dew-cell rather than to its speed of response, and can be markedly reduced by averaging the dew-point over a longer interval. In a typical period at Lerwick the standard deviation of departures of hourly mean dew-points measured by a dew-cell from those measured by an aspirated psychrometer was 0.22 degC, only half that of the hourly spot values (0.41 degC). Inspection of the records indicates that the more convenient period of a quarter of an hour would give almost as small a standard deviation.

Effect of ambient weather conditions. Laboratory investigation indicates that variations of wind speed should have only a small effect on the indicated dew-point, most of the effect occurring at wind speeds below 3 knots (≈ 1.5 m/s) at dew-cell level. An increase in wind tends to cool the element slightly. At certain stations it appeared that as the wind speed increased, the dew-points indicated by the dew-cell decreased relative to those indicated by the psychrometers, but at other stations no such effect was apparent. The shield has since been modified to the form shown in Plate I, and a wind-tunnel test confirms that wind effects can now be neglected. It might be expected that solar radiation would affect the dew-cell temperature since the equilibrium temperature depends on the rate of loss of heat to the environment. No consistent relation was found in a trial conducted at Lerwick in the summer of 1970, nor was any found in winter 1970/71, between the functioning of the dew-cell and the cloud amount. Thus the radiation shield is effective in shielding the dew-cell from short-wave radiation receipt and long-wave radiation loss. However, the difference between the dew-points indicated by the dew-cell and the aspirated psychrometer was found to depend markedly on the relative humidity. Typically, the difference between indicated dew-points (dew-cell minus psychrometer) increased by 0.8 degC as the relative

humidity fell from 100 per cent to 40 per cent, the dew-point remaining effectively constant. The effect has been confirmed in the laboratory. It is believed to result from the way in which the dew-cell loses heat from the thermal mass adjacent to the flange (see Figure 1) which is exposed to the air. The higher the relative humidity, the higher the dew-cell temperature compared with the air temperature, and so the cell loses heat more readily at high relative humidities than at low relative humidities. The calibration curve has been constructed for a relative humidity of 65 per cent, and corrections are therefore required for other relative humidities.

Since the dew-cell operates at an elevated temperature, it might be expected that, in a fog, droplets would be evaporated round the dew-cell so that the latter would read too high a dew-point. The relationship is more complex, however. In conditions of hill-fog and sea-fog (Lerwick), there is a marked increase of indicated dew-point as visibility decreases. In dense fog the dew-point is typically 0.3 degC higher than that indicated at a relative humidity of 100 per cent in the absence of fog. However, in radiation fog, in a relatively polluted atmosphere (Kew), no increase in indicated dew-point was found. This is thought to be a result of the very low liquid-water content of such radiation fogs, owing to the small droplet size which is nevertheless effective in reducing visibility.

Tests of the dew-cell in freezing conditions highlighted the difficulties of operating psychrometers in these conditions. A long 'tail' of large positive dew-point excesses of the psychrometer over the dew-cell was often noted, and was not balanced by corresponding negative differences. This results from an insufficient covering of ice on the ice bulb. Readings of dew-point indicated by the dew-cell thus tend to be lower than those indicated by the psychrometer when the temperature is below freezing-point, and are more reliable.

Overall comparison of dew-cells with psychrometers. Nine different dew-cells were tested against eight different psychrometers. A total of about 45 000 sets of observations was collected. The standard deviation of spot values taken hourly (five sets of comparisons) was about 0.4 degC while that of daily means (eight sets of comparisons) was typically about 0.3 degC. The mean differences between dew-cells and psychrometers at individual stations varied between +0.56 degC and -0.42 degC in a way not obviously related to the type of psychrometer (i.e. aspirated or naturally ventilated, or fitted with mercury-in-glass or electrical-resistance thermometers). The overall mean difference of dew-point (dew-cell minus aspirated-psychrometer) was -0.01 degC (four sets of comparisons); the difference for (dew-cell minus naturally ventilated mercury psychrometer) was -0.05 degC (seven sets of comparisons). The observed spread of systematic mean differences between the dew-cell and psychrometer readings is as much a function of the psychrometer performance as of that of the dew-cells; careful laboratory investigation suggests that real differences between individual dew-cells would contribute only half the spread. Great care has to be taken over the arrangements for measuring the temperature in both types of instrument, and some of the variation can be attributed to instabilities in the resistance thermometry.

Conclusions. The lithium chloride hygrometer is a suitable replacement for the wet-bulb thermometers in freezing conditions and is a useful instrument under all conditions. Its main limitations are that it needs to be periodically 're-doped' with lithium chloride solution (about once every two months) owing

to the effects of atmospheric pollution, and has to be immediately re-doped after a power failure lasting more than a few tens of minutes, failing which erroneous readings can result. It is also less accurate than a psychrometer in high humidities, particularly in fog. It uses too much power for battery-operated automatic weather stations, but the present generation of Meteorological Office Weather Observing Systems (MOWOS⁸) is mains-powered, and a mains supply is always available at synoptic stations. The dew-cell has now been officially accepted for operational use where a remote-reading device for measuring humidity is justified. MOWOS is already being equipped with dew-cells in addition to naturally ventilated psychrometers.

Acknowledgements. The author wishes to thank the staffs of the stations which took part in the field trials and in particular Mr J. B. Tyldesley, who wrote the first report on the trials. Thanks are also due to Messrs G. Cromarty and F. Lumb for their careful work in the laboratory.

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551.594.22:629.7

ELECTRICAL PHENOMENA OBSERVED AT NIGHT IN THE TROPICS FROM A HERCULES AIRCRAFT

By Squadron Leader N. LAMB
(Officer Commanding Meteorological Research Flight, RAE Farnborough)

Summary. While a Hercules W Mk2 was flying at night at flight level 200 off Dakar a series of vivid electrical discharges was observed on part of the aircraft's external instrumentation; these discharges were apparently associated with lightning.

On 12 August 1974 I was Captain of the Meteorological Research Flight Hercules W Mk2 taking part in a multi-aircraft mission in Project GATE. We left Dakar at 0520 GMT to transit at flight level 200* to a ship position at 09°N 22°W. The first 180 miles were uneventful and, although we were in cloud all the way, conditions were smooth with little or no icing. It was very dark. At position 12°N 20°W, the weather radar had shown cloud, but with no iso-echo returns, light turbulence and icing were experienced, and electrical disturbance was evident. At regular intervals of somewhere between 30 seconds and one minute, and lasting approximately three seconds, there appeared a colourful cascade of electrical discharges between the trailing edges of each of the four wind vanes and about 50 cm aft, where the nose probe begins to thicken. (The axes of rotation of the wind vanes lie in a plane perpendicular to the axis of the nose probe, and are symmetrically distributed above,

* i.e. at a height shown on the altimeter as 20 000 feet.

below, and to either side of the probe.) This was observed about three times, to be replaced, at approximately the same interval, by what appeared to be lightning in the cloud below and to the right. The co-pilot's impression was that it was below and to the left. A close watch on the nose probe showed that the tip began to glow yellow until, over a period of about three seconds, it reached a certain white intensity; the glow then disappeared simultaneously with the occurrence of what appeared to be distant lightning flashes. Static interference was heard in the headphones during each three-second period.

The phenomenon could not be observed on the forward-looking television cameras as there was too much interference on the screens at the time. A camera was brought forward in the hope of photographing the 'cascade' but unfortunately that particular phenomenon did not recur.

That the nose probe is liable to attract lightning in this manner had been shown by a previous incident which took place in March 1974 while the same aircraft was flying over the United Kingdom at 2000 feet and just below what appeared to be a layer of stratocumulus. The cloud just above where the strike occurred was darker than the general cloud in the area but it had not shown on the weather radar as a particularly active cloud. Damage to the aircraft was slight; one wind-vane was pitted, there was very shallow pitting on the stainless-steel pitot head and shaft, and the nose boom was peppered with small holes as far aft as the television-camera windows. The Lightning Research Department of the Royal Aircraft Establishment advised that with the Hercules W Mk2, the nose boom would be the place most likely to attract lightning.

AWARDS

L. G. Groves Memorial Prizes and Awards

In 1946 Major and Mrs K. G. Groves instituted three prizes to be awarded annually in memory of their son, Sergeant (Meteorological Air Observer) Louis Grimble Groves, R.A.F.V.R., of No. 517 Squadron, Coastal Command, who lost his life while flying on a meteorological sortie on 10 September 1945.

The L. G. Groves Memorial Prize for Aircraft Safety is awarded for the most important contribution made during the year towards the safety of aircraft and flying personnel. All members of the Royal Air Force are eligible for this prize, which is awarded on the recommendation of a board under the chairmanship of the Director of Flight Safety, Royal Air Force.

The L. G. Groves Memorial Prize for Meteorology is awarded for the most important contribution made during the year, either to the science of meteorology, or to the application of meteorology to aviation. All members of the Meteorological Office and the Royal Air Force are eligible. The prize is awarded on the recommendation of a board under the chairmanship of the Director of Research, Meteorological Office.

The L. G. Groves Memorial Award for Meteorological Observers is made to an officer employed on flying duties, or to a member of aircrew, service or civilian, who has been employed on meteorological observer duties, or other flying duties relating to meteorology, or to British or Commonwealth personnel

engaged in operational meteorology on ocean weather ships, for meritorious work or devotion to duty during the previous year. The award is made on the recommendation of a board under the chairmanship of the Director of Research, Meteorological Office.

In 1960 Major and Mrs Groves made a further generous donation to increase the values of the existing prizes and award and to set up a fourth to be known as the 'Second Memorial Award'. It is given, at the discretion of the Ministry of Defence, for meritorious work in any of the fields covered by the existing prizes and award, or in operational meteorology.

The 28th annual presentation of the prizes and awards took place on Thursday 7 November 1974 in the Main Conference Room, Ministry of Defence, Whitehall, and was presided over by the Vice Chief of Air Staff, Air Marshal Sir Ruthven Wade, K.C.B., D.F.C. Also present were Air Commodore D. F. M. Browne, C.B.E., A.F.C., Director of Flight Safety, Royal Air Force, and Dr B. J. Mason, C.B., F.R.S., Director-General of the Meteorological Office. It was for Major and Mrs Groves, who as in previous years presented the prizes, a doubly felicitous occasion since it was also their Diamond Wedding anniversary. (See Plates II-V.)

The Prize for Air Safety was awarded to Sergeant M. Dubey, Royal Air Force, Tern Hill, who devised a modification to the Mk 17/17a Life Preserver following an investigation into faulty operation. In proposing the modification Sergeant Dubey has made a worthwhile contribution towards the survival of aircrew obliged to abandon their aircraft over the sea.

The Prize for Meteorology went to Dr C. J. Readings of the Meteorological Research Unit, Royal Air Force, Cardington, with the following citation:

'As leader of a small scientific team based at Cardington, Dr C. J. Readings has been responsible for the development of techniques for the measurement of atmospheric structure from the cable of a tethered balloon, and for exploiting these techniques for the study of turbulence in the lower atmosphere. Comparisons with similar measurements by different techniques developed in the United States of America have shown for the first time that reliable measurements are being obtained of certain important but elusive quantities—the flux of heat, momentum and moisture through the lower atmosphere. Dr Readings has also made important contributions to the interpretation and analysis of these measurements which promise a greatly improved understanding of turbulence in the lower atmosphere.'

The Award for Meteorological Observers was won by Flight Lieutenant F. Robertson of the Meteorological Research Flight, Royal Aircraft Establishment, Farnborough. The citation states that:

'During his service with the Meteorological Research Flight, Flight Lieutenant Robertson's diligence and skill as a navigator has contributed directly to the success of the meteorological research particularly during the planning and execution of flights through wave-motion in the lee of mountains during project WAMFLEX. Flight Lieutenant Robertson's enthusiasm in studying the potentialities of the stable platform on the new Hercules aircraft has also enabled the capability of the aircraft for wind measurements to be exploited to the full.'

The Second Memorial Award was made to Flight Lieutenant D. R. Gasson, Royal Air Force, Lossiemouth, who had shown considerable resourcefulness in adapting the D Mk 1 parachute harness carried by the crews of Shackleton

aircraft, at present unsuitable for continuous wear, and therefore impracticable in an emergency with insufficient time to don the harness. Flight Lieutenant Gasson's proposals will significantly enhance the chances of survival for Shackleton crews obliged to abandon their aircraft in an airborne emergency.

Proxime accessit. Flying Officer Trudi Cant, Royal Air Force, Odiham received an air safety citation. She was, to the obvious delight of Major Groves, the first woman to have reached the 'top five'.

REVIEW

Dynamic meteorology, edited by P. Morel. (Lectures delivered at the Summer School of Space Physics of the Centre National d'Études Spatiales held at Lannion, France, 7 August–12 September 1970.) 245 mm × 165 mm, pp. 622, *illus.*, D. Reidel Publishing Co., P.O. Box 17, Dordrecht, Holland, 1973. Price: 115 Dfl.

This book is based on lectures delivered at a Summer School sponsored by the Centre National d'Études Spatiales held at Lannion, France, in 1970. The list of contributors—Phillips, Charney, Lilly, Monin, Morel and Queney—contains some of the most influential figures in dynamical meteorology in recent years.

The first section of about 90 pages is a succinct account of the principles of large-scale numerical weather prediction by Professor Phillips. The material is well known, apart possibly from the precise method of illustrating the initialization problem, which does not seem to have appeared elsewhere. The choice of topics and their presentation is impeccable.

The second series of lectures (150 pages) on 'Planetary fluid dynamics' by Professor Charney is more discursive. The bulk of it is concerned with solving particular problems, which have been identified in the atmosphere by analytical methods, for which questions of scaling, dependence on non-dimensional numbers and appropriate linearizations are fundamental concepts. The range of problems treated is very wide and the fact that Professor Charney has made definitive contributions to almost all of them is a measure of his immense influence on meteorological thought.

The remaining contributions are on rather more narrowly defined aspects of meteorology, allowing the authors a more leisurely presentation. Professor Lilly uses the mathematical theory of turbulence to expound the problems of subsynoptic-scale motions and their impact upon predictability, clear-air turbulence and convective parameterization. Professor Monin's account of the boundary layer follows familiar lines dependent on similarity theory as pioneered by Russian scientists and goes on to consider its application to planets other than the earth. The lectures by Professor Morel on data analysis and initialization are very clear, and based essentially on Gandin's theory of optimum interpolation. Finally, Professor Queney presents a fairly detailed mathematical treatment of the theory of mountain waves.

The book has been reproduced photographically from the typewritten text with the mathematics inserted by hand. This is obviously not ideal and occasions a larger number of editorial blemishes than normal; figures, for instance,

are not always sequential and sometimes have no numbers. However, it is usually clear and adequate for the essential purpose. We have to be thankful that the publishers have found a format that has enabled them to make such a distinguished set of lectures available to a wider public.

A. GILCHRIST

LETTER TO THE EDITOR

Association of British Climatologists—New Directory

I should like to draw the attention of readers of the *Meteorological Magazine* to the fact that a second Directory of British Climatologists is being prepared under the aegis of the Association of British Climatologists. It is intended to make this as comprehensive as possible, containing categorized information on climatologists in Britain, their affiliations, research interests and recent publications, and we hope that every scientist working in the field of climatology will be willing to contribute.

Anyone interested in being included in this Directory should contact me at the address below as soon as possible.

(PROFESSOR) S. GREGORY

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CORRECTIONS

Meteorological Magazine, September 1974.

Page 246, Figure 4: caption should read 'Contours of u_{10}/V_g in terms of R and V_g '.

Page 250, Table I: centre heading should read u_z/u_{10} .

Page 252, line 11: equation should read

$$\Delta_h V_g = \frac{h}{1000} \cdot \Delta V_g \equiv 3.3 \Delta_h T,$$

Page 253, Figure 10: centre right-hand horizontal axis with values 2–14 should be labelled u_{10} m/s.

Page 254, line 8: $u_1/u_{10} \approx 0.75$ should read $u_z/u_{10} \approx 0.75$.

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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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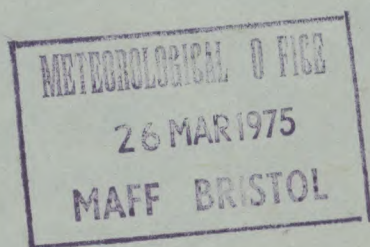
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REFLECTIONS ON SOME UNUSUAL YEARS

By J. M. CRADDOCK and M. J. WELLER

Summary. An analysis of the Lamb weather types for the years 1861–1970 suggests that although in most years the frequencies of the various types show only chance deviations from the long-term averages, the year 1872 and perhaps a few others deviate from the mean pattern in ways which are unlikely to arise by chance. The probability of occurrence of unusual years in future is discussed with reference to various rainfall records, and the suggestion is made that deviations of the general atmospheric circulation may operate to produce years about as wet as 1872 on average about once in 120 years.

Introduction. Although climate, and climatic changes, are usually discussed in terms of the values of meteorological elements averaged over periods of years, there are many applications in which the most useful climatic information is an estimate of the probability that some more or less extreme value will be exceeded. If past observations of the same kind can be fitted within reasonable limits of confidence by a suitable statistical distribution, then inferences may be made as to the probability of future extreme values, on the assumption that future values will conform to the same distribution, and this has often been done in the past. However, if the statistical distribution which covers most of the observations cannot be made to fit a few exceptional cases, then there is no reason to suppose that the distribution will be any more successful in estimating the probability of future extremes than it is in describing past observations. This article suggests that the probability of future occurrence of some of these unusual cases can be estimated only from the unusual cases themselves, and not from the statistics which describe the majority of past observations.

Inferences from Lamb's classification of daily weather types. The classification published by Lamb,¹ which now includes the years 1861 to 1970, is a revision of much earlier work on the same subject, in which every year has been treated by Professor H. H. Lamb in person, the years being taken in random order to minimize the risk of any unconscious change in standards during the months spent on the exercise. The detailed categories are grouped into the seven main weather types, which are used in the present analysis to describe the weather pattern each day within about a 10-degree square which includes the British Isles. Classifying the weather for a year involves looking at a sequence of at least 365 charts, one for each day, and observing the characteristic wind directions, motion of depressions, etc., and although opinions

may differ about the correct classification of an individual day, it is unlikely that another experienced synoptic meteorologist who repeated the work for a year would arrive at a significantly different result. A few days, averaging about 13 per year, are unclassifiable, and the mean frequencies of the seven types in the 110 years are shown in Table I. These means, which include virtually all the evidence on the subject which now exists, are the best estimates which can be made of the frequencies to be expected during an individual year.

TABLE I—FREQUENCIES OF LAMB'S DAILY WEATHER TYPES, WITH VALUES OF χ^2 , FOR SELECTED YEARS BETWEEN 1861 AND 1970

Year	W	NW	S	E	N	AC	C	χ^2
Mean*	93	18	27	28	31	91	64	—
1873	94	18	27	31	25	85	70	2.96
1953	100	16	23	18	28	119	49	18.58
1968	64	12	32	42	32	95	64	18.96
1877	115	29	20	26	27	56	81	32.55
1952	75	32	48	30	23	87	59	32.61
1887	73	19	43	22	19	124	51	34.09
1960	76	5	36	42	35	67	86	35.65
1921	124	8	17	18	32	113	42	36.39
1955	74	8	46	30	33	119	44	37.60
1923	129	28	31	25	26	52	66	37.68
1947	85	13	15	56	35	91	52	37.75
1924	94	16	16	23	54	66	89	40.06
1963	70	21	20	58	32	72	72	45.19
1872	101	15	29	26	45	38	100	58.64

AC Anticyclonic C Cyclonic * 1861–1970 inclusive

The expression $\chi^2 = \Sigma (O - E)^2/E$, where E is the long-term average, O the observed frequency, and the summation is over the seven categories, known as the chi-square statistic, is a common-sense measure of the extent to which the frequencies in any year differ on the average. Values of χ^2 are given in the last column of Table I for a year which closely resembles the average, two from the middle of the distribution, and for the 11 years among the 110 for which χ^2 is largest. If the annual rainfall for these 11 years is taken from the table of rainfall totals for England and Wales, published by Glasspoole,² and in an up-to-date form by Wales-Smith³ it appears that four of these years were very wet, two were very dry, and the rest not obviously exceptional. Average frequencies for these subgroups of years are given in Table II.

TABLE II—AVERAGE FREQUENCIES OF THE LAMB WEATHER TYPES FOR THE YEARS WHICH DIVERGE MOST FROM THE LONG-TERM MEAN, GROUPED ACCORDING TO THEIR ANNUAL RAINFALL TOTALS

	W	NW	S	E	N	AC	C
Long-term mean	93	18	27	28	31	91	64
Wet years 1872, 1877, 1924 and 1960	96.5	16.25	25.25	29.25	40.25	56.75	89.0
Dry years 1887 and 1921	98.5	13.5	30.0	20.0	25.5	116.5	46.5
Middling years 1923, 1947, 1952, 1955 and 1963	86.6	20.4	32.0	39.8	29.8	84.2	59.2

Table II shows that the wet years are characterized by excessive frequencies of the Northerly and Cyclonic weather types, and a deficiency of the Anticyclonic type. The dry years show excessive frequencies of the Anticyclonic weather type, and deficiencies in the Northerly and Cyclonic types, while the middling years, if they show anything, show an excess of the Easterly weather type which is in fact due entirely to the two years 1947 and 1963. Otherwise the frequencies, even though the years were chosen for their divergence from the average pattern, seem to conform surprisingly well to it.

Conversely, the other years in the rainfall record for England and Wales which had equally extreme rainfall totals also had high values for χ^2 , though not quite as high as those listed. This is strong evidence for an association between extreme values of the annual rainfall total in England and Wales and large departures of the frequencies of the Lamb weather types during the year from the long-term average, and of the two variables, the frequencies of weather types, though less familiar, are nearer to the general atmospheric circulation which produces them.

Estimating the 'equivalent number of repetitions'. The use of the chi-square statistic as a measure of the discrepancy between observation and expectancy suggests the question 'Do the 110 values of χ^2 fall into the distribution of chi-square with six degrees of freedom, as they should do if the 365 events sorted into seven categories were all independent?' The answer is that they do not do so, and the reason seems to be that the weather types which occur on successive days are not independent. This has the result of inflating the values found for χ^2 , and it may be possible, following Lewis and McIntosh⁴ to divide all the observed values of χ^2 by an 'equivalent number of repetitions' which brings the modified observations into agreement with expectation. This is done, using several trial factors, in Table III.

Table III suggests that the 'equivalent number of repetitions' is about 2.85, but the choice is not very critical. This factor has the effect of bringing the reduced values of χ^2 into satisfactory agreement with the distribution. Larger values of the factor produce an excess of years which conform too closely to the average, which is a common sign of overfitting, while smaller values produce larger numbers of deviant years. The factor 2.85 produces a small excess of large discrepancies, of which only one is individually significant, that for 1872. The observed value of χ^2 of 58.64, when divided by 2.85, has a probability of chance occurrence of only about 0.001. If this value is in fact due to chance, if, so to speak, the year 1872 is an ordinary member of the weather pack, it is rather surprising to find it in the sample of 110 years investigated. However, there is the possibility that 1872 is *not* an ordinary member of the weather pack, but a kind of joker, produced by some vagary of the general atmospheric circulation with a probability of something between about 1/55 and 1/220, in which case its occurrence once in 110 years is perfectly natural. Before trying to decide between these alternatives, it is worth while considering some other evidence.

Discussions of the annual rainfall at Bidston. The annual rainfall totals recorded at the Liverpool Tidal Observatory at Bidston for the years 1871 to 1930 were discussed by Doodson and Bigelstone⁵ in a paper which is remarkable for the way in which the senior author, Dr Doodson, treated his observations

TABLE III—AGREEMENT OF CORRECTED χ^2 WITH DISTRIBUTION OF CHI-SQUARE WITH SIX DEGREES OF FREEDOM

Range	0.5	5-10	10-20	20-30	30-50	50-70	70-80	80-90	90-95	95-100	χ^2
Upper limit	1.635	2.204	3.070	3.828	5.348	7.231	8.558	10.645	12.592		
Expected	5.5	5.5	11	11	22	22	11	11	5.5	5.5	
Factors											
3.255	6	5	22	8	24	19	11	7	6	2	16.24
	0.05	0.05	11	0.82	0.18	0.41	0	1.45	0.05	2.23	
3.184	5	5	19	11	22	22	9	8	7	2	
	0.05	0.05	5.82	0	0	0	0.36	0.82	0.41	2.23	9.74
3.15	5	5	19	11	22	19	12	8	6	3	
	0.05	0.05	5.82	0	0	0.41	0.09	0.82	0.05	1.14	8.43
3.05	4	4	18	12	24	17	11	9	8	3	
	0.41	0.41	4.45	0.09	0.18	1.14	0	0.36	1.14	1.14	9.32
2.95	4	4	14	15	23	17	12	9	6	6	
	0.41	0.41	0.82	1.45	0.05	1.14	0.09	0.36	0.05	0.05	4.83
2.85	3	4	14	13	24	18	10	10	7	7	
	1.14	0.41	0.82	0.36	0.18	0.73	0.09	0.09	0.41	0.41	4.64
2.75	3	3	12	15	23	18	10	12	6	8	
	1.14	1.14	0.09	1.45	0.05	0.73	0.09	0.09	0.05	1.14	5.97
2.65	3	3	8	19	20	19	8	16	5	9	
	1.14	1.14	0.82	5.82	0.18	0.41	0.82	2.27	0.05	2.23	14.88

Note. x_1 - x_8 frequencies of modified χ^2 values.
 y_1 - y_8 contributions to χ^2 .

in a way reminiscent of an old-fashioned schoolmaster dealing with an unruly class, and after considerable discussion, continued to believe in the relevance of a statistical distribution which did not agree with the facts. Zoch⁶ made a somewhat less controversial analysis of the same data, while Reynolds⁷ considered the longer series of annual totals running from 1867 to 1951, and concludes that if these rainfall totals are assumed to belong to the normal frequency distribution, then the rainfall total observed in 1872 should occur only once in 16 500 years. He does not draw the conclusion, which follows from the principles in paragraph 20 of *Fisher's statistical methods for research workers*,⁸ that this is a good reason for thinking that the normal distribution is not a suitable one for describing these data, and nowhere in the discussions is there any mention of a point which will occur to any present-day hydrologist, namely, that Bidston is sited in a pronounced rain-shadow as regards rain areas approaching from the west, but has no such protection against rain from the north-west, or in cyclonic situations, such as were unusually frequent in 1872, so that anomalous rainfall of the kind observed is something which might well have been expected from a knowledge of the frequencies of the various weather types. The statistical discussions have some historical interest, as illustrations of the attitudes of scientists over the years, but the practical moral is surely that when faced with what seems an extraordinary occurrence, it is necessary to consider as many as possible of the relevant facts.

The incidence of heavy rainfall, considered as a rare event. Reynolds⁷ states that during the 85 years from 1867 to 1951 there were 106 days for which a rainfall total of over one inch was reported, which gives an annual average of 1.247 days of rain exceeding this limit. This average can be used, as in *Fisher's statistical methods for research workers*, paragraph 15, to estimate the number of years, among the 85, which may be expected to have 0, 1, 2 etc. days of heavy rain. These expected frequencies are given together with the observed frequencies reported by Reynolds⁷ in Table IV.

TABLE IV—OBSERVED AND EXPECTED FREQUENCIES OF YEARS HAVING THE GIVEN NUMBERS OF DAYS WITH RAIN TALLING OVER ONE INCH

Number of rainy days								Total
	0	1	2	3	4	5	6	
Observed	27	28	18	9	1 (1947)	1 (1877)	1 (1872)	85
Expected	24.4	30.5	19.0	7.9	2.5	0.6	0.1	

The agreement between expectation and observed values is very good, except that a year with six days with over one inch, which is the number found in 1872, should occur only once in 850 or so years. The general agreement is noteworthy, because the basic conditions for the validity of the Poisson distribution, that each day should be exposed to the same risk, and that the occurrence of the event on one day should not affect its probability on another, are only approximately satisfied when the risk concerned is that of having rainfall exceeding one inch. Indeed, Reynolds gives monthly frequencies which show that the risk is about constant during the months of July and August, and higher than the risk at other times of year, but it appears from Table IV that this is enough to bring all years except 1872 into very good agreement with the

distribution. Since, as mentioned already, in 1872 Bidston was exposed to an unusually high number of rain-bearing situations without the benefit of its usual orographic protection, an increased risk in that year is not surprising.

The evidence from ancient years. Another way of increasing the amount of evidence on unusual years is to look back at the years before 1861. There are at present no series of charts for these earlier years from which the frequencies of Lamb weather types can be found, although there are plenty of early records from which charts could be prepared.* However, there are monthly rainfall records going back more than 100 years before 1861. The first comprehensive collection of such records seems to have been made by Symons,⁹ but the best-known modern reduction is the series of England and Wales monthly rainfall published by Glasspoole,² of which the annual totals, brought up to date, have been republished by Wales-Smith,³ who has also published a homogenized series of monthly rainfall estimates, or observations, for Kew for the period 1697 to 1970.¹⁰ Manley¹¹ has published a similar series for Manchester for the period 1765 to 1971. The wettest and driest years during these periods, according to the three reductions, are given in Table V.

TABLE V—WETTEST AND DRIEST YEARS IN PERIODS STATED ACCORDING TO THE REDUCTIONS OF GLASSPOOLE, MANLEY AND WALES-SMITH

England and Wales Glasspoole ² 1727-1973		Manchester Manley ¹¹ 1765-1971		Kew (London) Wales-Smith ³ 1697-1970	
Wet	Dry	Wet	Dry	Wet	Dry
1872 50+	1738 26+	1792 53+	1780 26+	1903 38+	1699 16+
1852 49+	1750 26+	1872 51+	1788 26+	1824 36+	1743 16+
1768 46+	1864 26+	1789 49+	1844 26+	1821 34+	1840 16+
1960 46+	1887 26+	1954 47+	1855 26+	1852 34+	1864 16+
1903 45+	1780 25+	1787 46+	1902 26+	1841 33+	1723 14+
1841 44+	1743 24+	1823 46+	1904 26+	1879 33+	1731 13+
1848 44+	1921 24+	1836 46+	1937 26+	1915 32+	1714 12+
1877 44+	1741 23+	1877 46+	1941 26+	1927 32+	1921 12+
1882 44+	1788 23+	1768 45+	1955 26+	1768 31+	
1912 44+	1731 22+	1848 45+	1826 25+	1819 31+	
		1852 45+	1933 25+	1828 31+	
		1882 45+	1887 21+	1860 31+	
		1931 45+			

Note. Rainfall amounts are given in inches. 49+ implies in range 49.0 to 49.9.

Comparison between the three series shows that while 1872 seems to have been very wet in Lancashire, and in the area represented by Glasspoole's reduction, it was not outstandingly so in the London area. There are several similar instances. Bearing in mind how different regions of the country are affected by different large-scale weather types, the question arises whether Glasspoole was attempting too much in trying to provide figures typical of the country as a whole. He himself states that the estimates before 1815 are less reliable than those for later years, and if it is assumed, for example, that Glasspoole's estimates for years before 1800 are too low by about 10 per cent, then the year 1768 becomes a candidate for being the wettest ever. Apart from this, 1852 seems to have been a very wet year over the whole country. At Manchester, 1792 appears to be wetter than 1872. At the other end of the

* But now see: KINGTON, J. A.; *Met. Mag., London*, 104, 1975, pp. 33-52 and *Weather, London*, 30, 1975, pp. 21-24 (Editor).

scale, the very dry year at Manchester, 1887, would appear to be extremely improbable, if the internal evidence provided by Manley's reduction was all the evidence available, but the appropriate volume of *British Rainfall* shows it to have been a well-authenticated occurrence which was discussed at the time, and was produced, like many other similar events, by relatively small modifications of the general atmospheric circulation. It is, in our opinion, wrong to imply the extreme improbability of any event which has happened within a comparatively short period. When an event has happened only once within the rather short period covered by modern observations, there is real difficulty in estimating its probability of occurrence, and the only alternative to waiting—possibly for centuries—until it has had time to repeat itself, is to look backwards for any evidence which may be gleaned from earlier years.

The extent of early records. Table VI which is condensed from Symons⁹ gives a good idea of the amount of basic information which was known in his day, and although it applies specifically to rainfall records, shows the general increase of interest in meteorological topics from the seventeenth century onwards. Until about 1770, there was only a trickle of information, which, as Symons remarks, represents work carried out by first-class men, and which was enough to establish the broad facts about the conditions under which sensible rainfall and other measurements can be made. Before that time, an estimate, for example, of the monthly rainfall for England and Wales is suspect not only because of doubt as to exposures, etc., but also because of the shortage of information of any kind. For example, it is too much to expect the monthly rainfall measured in Rutland to provide much evidence about the actual rainfall in Devonshire, however good the instruments and the observer. After 1770 there is a great deal of information, much of which has never been used, even now, because it is awkwardly placed, hidden in libraries, or in manuscripts which cannot easily be copied or collated.

Symons⁹ provides enough details of the stations known to him for each year from 1697 onwards. Glasspoole² only gives, for each year, the number of stations used in his reduction. These stations are usually rather more numerous than those which were known to Symons. However, the collection of copies of ancient records within the Meteorological Office has continued over the years, and the 10-year books, as they are called, which are held by the Agriculture and Hydrometeorology Branch of the Meteorological Office, now contain considerably more ancient data than were known to Glasspoole. The entries are undated, and usually give some reference to the source, but none to the copier, so that there is no way of making sure which records were available to which workers. However, it appears that further reductions, like those of Manley¹¹ and Wales-Smith³ are possible for other areas, such as the east Midlands, Devonshire and the Carlisle area. If, as the records suggest, Glasspoole had to rely on stations in the eastern half of England for almost all his estimates before 1780, this is a good reason for caution in using the earlier part of the monthly rainfall record for England and Wales.

Discussion. The analysis of the observed frequencies of the seven main Lamb weather types during the years 1861 to 1970 suggests that most years conform within statistical limits to the mean pattern, given an 'equivalent number of repetitions' of about 2.85, and that most of the minority of years which

TABLE VI—ANALYSIS OF RAINFALL RECORDS KNOWN TO SYMONS⁹ FOR STATIONS IN GREAT BRITAIN

Period	Number of station-years	Period	Number of station-years
Up to 1679	3	1770-1779	84
1680-1689	8	1780-1789	133
1690-1699	10	1790-1799	176
1700-1709	14	1800-1809	151
1710-1719	7	1810-1819	209
1720-1729	8	1820-1829	401
1730-1739	36	1830-1839	1 029
1740-1749	11	1840-1849	1 777
1750-1759	20	1850-1859	3 663
1760-1769	39	1860-1864	3 693

do not conform give rise to weather which is unusual in some way, particularly as regards rainfall. The use of the Poisson distribution on the numbers of years with from 0 up to 6 days with rainfall exceeding a threshold value confirms the suggestion that the year 1872 stands out from the rest among Reynolds's Bidston data. This is a technique for finding unusual years which might well be used more widely, since it is very easy to apply. Comparison of the reduction of long-period values of annual rainfall published by Glasspoole,² Manley¹¹ and Wales-Smith³ shows that there are considerable regional differences, but also that at least two other years since 1727, namely 1768 and 1852 rival 1872 in being very wet over a large part of the country. If these were associated with departures of the frequencies of the Lamb weather types from the 110-year averages comparable with the departures observed in 1872, the inference would be that the general circulation is liable to produce deviations of this size about once in 120 years. To the criticism that we cannot be sure about the character of the weather types in those early years, the answer is that we can at least try to appraise the evidence which exists. There may be no resources to carry out a systematic analysis of data for *all* years in the instrumental era before 1861, but it may still be worth while examining the outstanding years, which may throw some light on the probabilities of extreme conditions in future. The long-period records published by Manley and Wales-Smith, which refer to limited areas which may be expected to respond in much the same way in any given weather situation, agree better with the present thinking than Glasspoole's reduction, in which the basic data are weighted towards different areas in different epochs. The question whether the apparent climatic change in Glasspoole's data, between drier years in the 1700s and wetter years since, is real, or a product either of a statistical accident, or of imperfect reductions of the early data, lies outside the scope of this paper, but may well be answered by new statistical methods, and extra data, which have become available since Glasspoole's publication. A general conclusion is that until more is known of the capabilities of the general atmospheric circulation in imposing local weather regimes, either by mathematical modelling, or by examining data from the earlier part of the instrumental record, it will remain hazardous to attempt, by statistical means, to estimate the probabilities of extremes which have not occurred during the period of full observations.

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PRELIMINARY RESULTS FROM A GRAVIMETRIC RAIN-GAUGE

By H. E. PAINTER

Summary. Rain recorded by a gravimetric rain-gauge has been measured and compared with the daily amounts collected in a standard 5-inch Mk 2 gauge with its rim 30 cm above the ground, in two types of gauge with their rims flush with the ground, and in a 750-cm² gauge with its rim 45 cm above the ground and fitted with a tipping-bucket mechanism. The relative inefficiencies of these gauges compared with the gravimetric gauge are clearly shown and corrections for daily rainfall amounts are given for these various types of gauge.

Introduction. The amount of rainfall collected by the conventional type of rain-gauge is generally less than the actual rainfall at the site of the gauge; this effect arises from various causes such as evaporation, adhesion of rain to the gauge, in-splash and out-splash, but by far the greatest factor is that due to the exposure to the wind, which generally causes a bigger error than all the other causes combined, see for example Kurtyka.¹ Various attempts have been made to eliminate or reduce the effect of the wind on the catch of a gauge. One such method is to mount the gauge with its rim level with the ground and to surround it with an artificial surface to minimize the effect of in-splash. Gauges mounted like this together with their surrounding surfaces can, however, still cause wind eddies which affect their catches. Even if everything else were perfect the hole in the ground made by the collecting funnel would be enough to change the wind flow over the surface of the ground. As part of a programme carried out by the Meteorological Office to assess the performance of rain-gauges, a recording gravimetric rain-gauge was developed and installed at Kew Observatory. This instrument has been described by Crawford² and now that a considerable amount of data has been obtained from it, the results of comparisons of simultaneous rainfall measurements from various gauges are here presented.

Rain-gauges. The gravimetric rain-gauge has a 1.21-m diameter pan mounted on a weighing machine placed in a concrete pit in the ground so that the rim of the pan is level with the surrounding ground. About 2.5 cm below the rim of the pan is a stainless steel mesh covered by a layer of small granite chips. An annular area extending 2 m from the rain-gauge pan is also covered with granite chips so that this area and the pan form a homogeneous surface apart from a small gap between the pan and the concrete pit. The weighing machine automatically measures the weight of the pan and its contents; this weight is converted into a millivolt analogue which is registered on a recorder.

Six other gauges were used in this comparison. Three were standard 5-inch Mk 2 rain-gauges with their rims 30 cm above the ground. Two standard 5-inch Mk 2 gauges were also mounted with their rims flush with the ground; these will be referred to as 'flush gauges'. One of these was in a 23-cm deep square pit with sides of 120 cm in length which was covered with a plastic grid with squares of side 5 cm. The depth of the grid is 5 cm and its top surface is level with the rim of the gauge. The base of the pit is composed of small stone chippings. The top edges of the grid were chamfered on the sides farthest from the rain-gauge so that drops hitting these edges would be deflected away from the gauge. This gauge is of the type recommended by the World Meteorological Organization.³ The second flush gauge has a splash-reducing surround suggested by Bleasdale.⁴ This is an array of thin green metal slats as used in venetian blinds. These slats are fixed to radial bars projecting from just beyond the rim of the gauge out to a distance of 61 cm. The slats are inclined at 45° to the horizontal and are so placed that splashes will tend to be directed away from the gauge. Below the slats is a gravel bed so that when the rain runs off the slats it is drained away. Several accounts^{5,6} describe flush gauges with this type of splash-reducing surround, but with an array of nine gauges; for this comparison only one gauge was used.

The remaining rain-gauge was a Meteorological Office tipping-bucket gauge with a funnel made of glass-fibre laminate of area 750 cm² and with its rim 45 cm above the ground.

Two of the standard 5-inch gauges were used for the routine Observatory measurements of rain and were read twice daily at about 5 minutes before the nominal observing times, whether it was raining or not. The third standard 5-inch gauge together with the WMO flush gauge and the tipping-bucket gauge were installed especially for this comparison and were read once daily at about 09 GMT. If, however, it was raining the reading of these three gauges was deferred until the rain had stopped. Occasionally the readings were deferred for a whole day and so the amount of rainfall in the comparisons covered a period of two days. The venetian-blind flush gauge had been installed for some years and was used in connection with measurements of evaporation from tanks. This gauge was read when the evaporation readings were made, which was usually at about 10 GMT. If the rainfall was heavy at the nominal reading time these measurements were deferred. If there was rain whenever any of these rain-gauges were being read the exact time of the measurement was noted.

These gauges are in the grounds of the Observatory which itself is in flat open park-land. A detailed description of the site is given in the *Observatories' Year Book 1965*.⁷ To the north and north-west of the gravimetric gauge are shrubs and small buildings rising to about 6 m at a distance of about 30 m. The largest obstructions to the gauges are two trees rising to 30 m between bearings

of 190° and 210° from the gravimetric gauge at a distance of 100 m. Otherwise, apart from instruments, the site is clear. Table I gives the nominal times of reading of the various gauges and their locations with respect to the centre of the gravimetric rain-gauge, hereinafter abbreviated to GRG. The second column of the table gives abbreviated titles of the other gauges and these abbreviations will subsequently be used.

Measurements. Rain in the 5-inch gauges was measured in the usual way to the nearest 0.1 mm by pouring it into a graduated glass measure. The rain in the TB gauge was registered by an electromagnetic counter, each increment in the count corresponding to 0.202 mm of rain. A few readings from this gauge had to be discarded as they were obviously in error, and in addition the instrument was out of action for several days. The output of the GRG was recorded on a 10-inch wide strip-chart running at one inch an hour. For most of the period the full-scale range of the recorder was equivalent to 30 mm of rain. For the first three weeks of September 1972 the full-scale range was 50 mm; from 26 January to 21 May 1973 the full-scale range was 18.4 mm. The recorder registers the rain every minute. The chart is divided into 100 divisions and can be read to a tenth of a division. The sensitivity, the sampling time, and the chart speed can all be varied. The settings of these variables will determine the degree of discrimination and the accuracy to which rain, dew, evaporation from the pan, and the rate of rainfall can be measured. It will be seen that, for most of the period of this comparison, the gain and loss of water could be measured to within 0.03 mm.

The rain was measured for each hour GMT during which it occurred. No account was taken of evaporation which showed between rainfall events, i.e. only increases in weight were measured. (A 'rainfall event' signifies an occurrence such as an individual shower or period of frontal rain.) Since the times at which the other gauges were read were known the GRG was read at these precise times. This, of course, was only important if any of the other gauges were read while it was raining. Occasionally, when rain was recorded, dew also was recorded at other times of the day; this was always added to the rain amount since the funnel gauges also collect dew. Two days when moderate snow fell have been excluded from the analysis. Six days on which part of the catch was hail have been included. For this analysis comparisons were only made if the corresponding daily rainfall amount measured by the GRG was at least 1 mm. For gauge A the daily period was taken from 09 GMT; for gauge B the period was taken from 18 GMT; for both of these gauges daily rainfall values could include the aggregate of two readings.

Although a strict comparison was made between each gauge and the GRG, the rainfalls measured by the various gauges were not always derived from the same rainfall events because the measurements were taken at different times. The aggregates, however, over the whole period were approximately the same for most of the gauges. Readings were taken from September 1972 to February 1974. The GRG was not always operative throughout this period as it was removed at times to enable modifications to be carried out; in addition the record was lost several times because it went beyond the limits of the scale.

Gauge A was found to be 0.5 per cent over-size in area, and gauges C and WMOF were 0.2 per cent under-size. The aggregate totals were accordingly corrected, and individual daily readings of gauge A were corrected when they exceeded 10 mm.

The results of the comparisons are shown in Table II. The first part of this table gives the aggregate rain for all the daily values considered, i.e. when the GRG measured at least 1 mm of rain. Following the method of an earlier comparison of rain-gauges by Clarkson⁵ at Easthampstead near Bracknell, the daily variation of rainfall is given by the regression equation of \bar{Y} (the catch of the comparison gauge) on G (the catch of the GRG) for the various rain-gauges, together with the 95 per cent confidence limits of the regression. The most probable value of \bar{Y} for a 10-mm rainfall measured in the gravimetric gauge is given as a percentage ratio. The lower portion of the table gives the regression equations of \bar{Y} for gauges A and TB on the 5-inch standard gauge C, these being directly comparable with gauges compared by Clarkson.⁵ In order to compare the readings of the two 5-inch gauges a selection had to be made so as to restrict the number of days on which both gauges were measuring the same rainfall irrespective of the different times of day at which they were read.

Reference rain-gauge. When the results from two instruments simultaneously measuring the same element are compared all that can be assessed is the performance of one relative to that of the other. If one instrument is used as a reference it is required that its accuracy be within acceptable limits. The GRG has been developed as a reference rain-gauge as suggested by Crawford.² Although it is difficult, if not impossible, to demonstrate that any rain-gauge actually measures the amount of rain that would have fallen on the ground in the absence of the gauge, the author considers that, for the GRG, the factors which are known to give rise to the errors of conventional types of gauge have been considerably reduced. The construction of the collecting area of the GRG together with its surrounds has been designed to affect the airflow over the instrument as little as possible, and also to minimize the net effect of splashing. As mentioned earlier the exposure of the conventional gauge has been the source of its biggest errors, and as will be shown later even mounting funnel gauges flush with the ground fails to eliminate all errors due to exposure. By the construction of the GRG, its catch must be less affected by the wind than that of the other types considered here. Even if there is an inequality between in-splash and out-splash in the GRG, the relatively large size of the pan will further reduce this effect upon rainfall measurements.

With regard to other sources of errors in rain-gauge measurements, adhesion of water to the instrument obviously has no effect on the GRG. Two forms of water exchange that affect rainfall measurements are demonstrated by the GRG: these are evaporation and the deposition of dew. Since any rain-gauge introduces an artificial object in the ground, the deposition of dew and the evaporation of water from a gauge will vary from instrument to instrument and will differ from what takes place on the neighbouring natural surface. A supplementary instrument or observation of 'weather' may be needed to determine whether a slight increase in weight of the GRG is caused by dew or by light rain. Generally these will not occur together so they can be isolated when one examines the GRG record. Evaporation from the pan is often recorded but this again can be isolated for periods when it is not raining, since the measurement of rain consists of the summation of the record when the weight is increasing. If evaporation occurs during rain the GRG measures the net increase in weight. Light rain has occasionally been observed when the GRG showed a continuing loss of weight. It is doubtful whether, in these circumstances, other gauges

TABLE I—DETAILS OF RAIN-GAUGES USED IN COMPARISON

Gauge	Abbreviated title	Area <i>cm</i> ²	Height of rim above surface <i>cm</i>	Approximate times of reading GMT	Distance <i>m</i>	Location with respect to GRG Bearing °
Gravimetric	GRG	115.0 × 10 ³	0	—	—	—
Standard Mk 2	A	126.7	30	0855, 2055	22.1	232
Standard Mk 2	B	126.7	30	0555, 1755	22.1	242
Standard Mk 2	C	126.7	30	0900	13.5	16
WMO flush	WMOF	126.7	90	0900	4.4	177
Venetian-blind flush	VF	126.7	0	1000	13.9	247
Tipping-bucket	TB	750	45	0900	13.4	5

TABLE II—VARIABILITY OF CATCH OF RAIN-GAUGES AT KEW FOR AGGREGATE TOTALS AND FOR DAILY RAINFALL AMOUNTS FOR WHICH THE GRAVIMETRIC GAUGE RECORDED AT LEAST 1 mm

Comparison gauge	<i>N</i>	Aggregate rainfall Comparison gauge <i>millimetres</i>	GRG	Percentage of catch of GRG	<i>E</i>	<i>P</i> <i>per cent</i>
5-inch standard A	101	461.0	495.3	93.1	$\bar{r} = 0.967 G - 0.167 \pm 0.506$	95.0 ± 5.1
5-inch standard B	100	440.8	475.5	92.7	$\bar{r} = 0.966 G - 0.191 \pm 0.529$	94.7 ± 5.3
5-inch standard C	92	436.8	474.6	92.0	$\bar{r} = 0.956 G - 0.194 \pm 0.420$	93.7 ± 4.2
WMOF	92	459.4	474.6	96.8	$\bar{r} = 0.993 G - 0.138 \pm 0.389$	97.9 ± 3.9
VF	100	477.8	486.3	98.2	$\bar{r} = 1.021 G - 0.193 \pm 0.502$	100.2 ± 5.0
TB	79	362.7	388.7	93.3	$\bar{r} = 0.951 G - 0.089 \pm 0.554$	94.2 ± 5.5
5-inch standard A	56	266.1	Gauge C	Percentage of catch of gauge C	$\bar{r} = 1.005 S + 0.050 \pm 0.387$	101.0 ± 3.9
TB	78	359.9	263.8 356.7	100.9 100.9	$\bar{r} = 0.985 S + 0.120 \pm 0.516$	99.7 ± 5.2

N Number of daily rainfalls each of which was recorded as at least 1 mm in the GRG.

G Amount collected in comparison gauge.

S Amount collected in GRG.

E Regression equation of \bar{r} on *G* (or *S*) for daily rainfalls, \pm the 95 per cent confidence limits of \bar{r} .

P Most probable percentage \bar{r}/G (or \bar{r}/S) \pm the 95 per cent confidence limits, for a rainfall of 10 mm in the GRG (or gauge C).

would have detected any precipitation. Evaporation, during rain, will occur from funnel gauges and also from natural surfaces, and from the hydrologist's point of view the net water gain may be more useful than the quantity of water from precipitation, but the meteorological definition of precipitation does not take into account any evaporation during precipitation. Any deficiency in the water catch during rain caused by evaporation will therefore cause an error in the GRG measurement. As is shown later all the other gauges on average produce deficits compared with the GRG and any error caused by evaporation from the GRG will enhance these deficits.

Although the errors of the GRG are not quantified the author considers that it will measure rainfall more accurately than the other gauges here described, and the GRG is therefore being used as a reference gauge to which the other gauges can be compared.

Discussion. It is seen from Table II that the three standard 5-inch gauges agree in their aggregate catches to within ± 0.6 per cent and that the 750-cm² gauge with a tipping bucket is in close agreement with the 5-inch gauges, as was previously found at Easthampstead.⁶ The scatter about the GRG measurements of the daily values derived from the two gauges A and B, which were used for routine observational purposes, was slightly greater than that of the daily values from gauge C but this would be accounted for by the fact that the values for A and B were often the aggregate of two measurements. For the same reason the comparison between two 5-inch standard gauges at Kew shows slightly more scatter than do the Easthampstead comparisons. One might have expected that the aggregate readings from gauges A and B would have been slightly lower than the corresponding readings from gauge C owing to losses when the former gauges were read during rain, and it therefore seems probable that any difference between these gauges is due either to slight differences of exposure or simply to experimental error. The WMOF gauge shows less scatter than the VF gauge, which can perhaps be attributed to their different splash-reducing surrounds. Alternatively, as discussed later, there is a possibility that the VF gauge is receiving some in-splash which would add another variable to the VF catch and so increase its scatter relative to that of the GRG. From Table II it is immediately obvious that all the gauges, including the flush gauges, are catching less rain than the GRG. The raised gauges collect in the aggregate about 7 per cent less rain, and the flush gauges about 2 to 3 per cent less than the GRG.

Gauge C is considered to be a typical 5-inch gauge with its rim at 30 cm, and the results of its comparison with the GRG are shown in Figure 1 where the ratio of the catch of the GRG to that of gauge C is plotted against the daily catch of gauge C. This figure represents the data used for the regression equation plotted in a form that emphasizes the differences at small daily rainfalls. Similar graphs were plotted for the two flush gauges and for the TB. These graphs showed similar scatter about their mean curves. In Figure 1 the values for which the precipitation included hail as well as rain have been plotted with distinguishing symbols. In all cases the hail was only a small part of each daily catch, and as can be seen from the plots they do not show any marked departure from the mean curve; hence these days have been included in the analysis.

Since the GRG is being used as a reference gauge the curve plotted in Figure 1 gives mean correction factors for daily rainfalls from gauge C. The

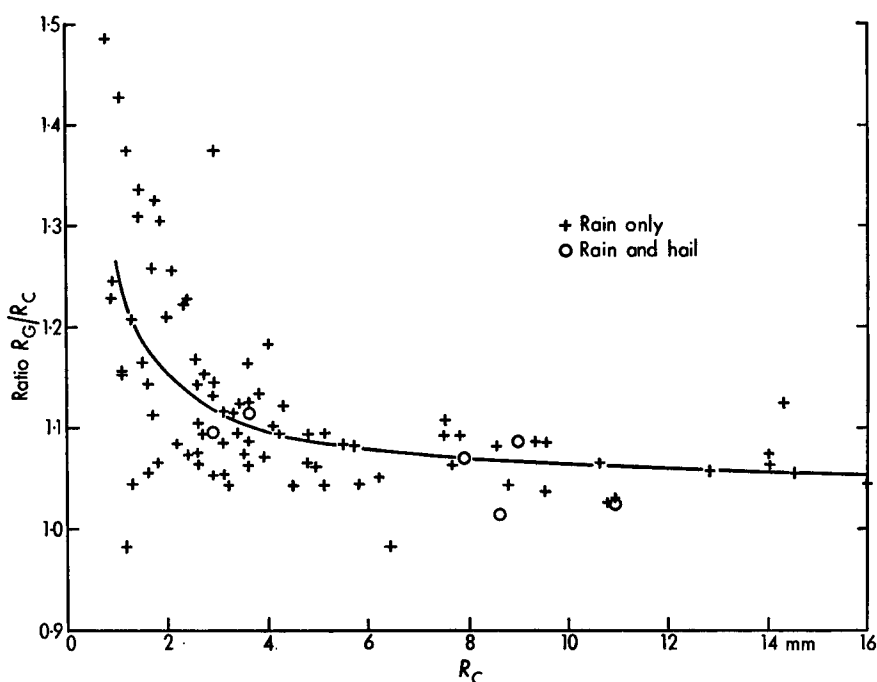


FIGURE 1—VARIATION OF RATIO (R_G/R_C) WITH R_C , WHERE R_G IS THE DAILY RAINFALL AS MEASURED BY THE GRAVIMETRIC RAIN-GAUGE (GRG), AND R_C IS THE DAILY RAINFALL AS MEASURED BY THE STANDARD GAUGE C

mean curves for each of the four types of gauge are shown in Figure 2. These curves are, in fact, the regression equations of the GRG on the comparison gauges plotted in the form appropriate to the axes chosen for Figures 1 and 2. By changing round the order of the regressions the equations now give mean correction factors for daily rainfalls for each of the comparison gauges. These equations for the four gauges together with their 95 per cent confidence limits are given in Table III in which R_x is the rainfall given by the comparison gauge and \bar{Y} is the corrected rainfall, i.e. that which would have been expected in the GRG.

TABLE III—CORRECTED DAILY RAINFALL (\bar{Y}) DERIVED FROM CATCHES OF VARIOUS GAUGES (R_x) WITH 95 PER CENT CONFIDENCE LIMITS

Gauges

5-inch standard	$\bar{Y} = 1.042 R_x + 0.220 \pm 0.436$
WMOF	$\bar{Y} = 1.005 R_x + 0.151 \pm 0.392$
VF	$\bar{Y} = 0.974 R_x + 0.211 \pm 0.485$
TB	$\bar{Y} = 1.045 R_x + 0.123 \pm 0.580$

Note. Measurements are expressed in millimetres.

The deficits in the rain catches of all these gauges compared with those of the GRG are immediately apparent from Figure 2. The two flush gauges and the standard 5-inch gauge at 30 cm are all of the same type and they each exhibit

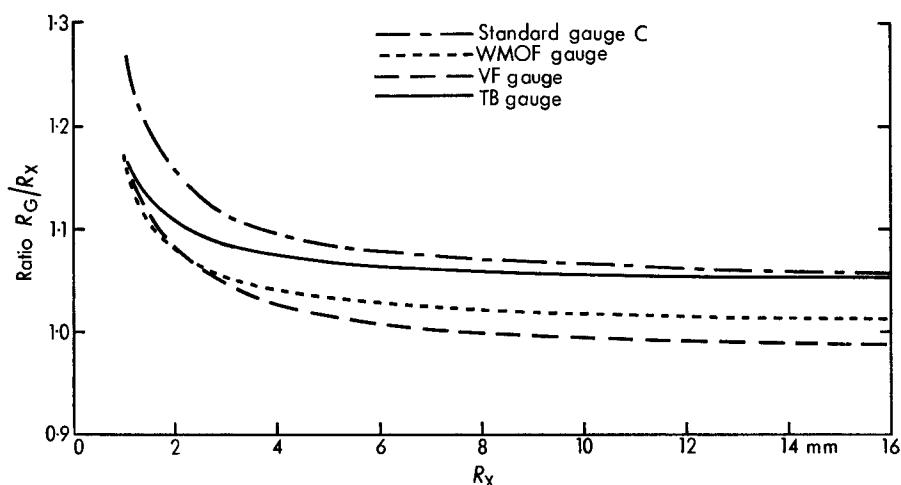


FIGURE 2—VARIATION OF RATIO (R_G/R_X) WITH R_X , WHERE R_G IS AS DEFINED IN CAPTION TO FIGURE 1, AND R_X IS THE DAILY RAINFALL AS MEASURED BY GAUGE X, WHERE X IS ONE OF THE FOLLOWING:

- (i) A STANDARD GAUGE (C)
- (ii) A WMO-RECOMMENDED GAUGE MOUNTED FLUSH WITH THE GROUND (WMOF)
- (iii) 'VENETIAN-BLIND' FLUSH-MOUNTED GAUGE (VF)
- (iv) A TIPPING-BUCKET GAUGE (TB)

the same shape of graph but with a displacement of 5 to 7 per cent between the values corresponding to the flush types and those corresponding to types with standard exposure. The range of values for the TB gauge is smaller than those of the other gauges, which perhaps can be attributed to the greater diameter of the funnel of this gauge. Especially noteworthy is the difference between the two flush gauges; whereas the WMOF shows a deficit over the whole range of rainfalls considered, the VF actually shows an increase in catch over the GRG at large daily rainfalls. As occasionally particles of sand, from the gravel bed below the slats, are found in the funnel, it is evident that there is a certain amount of in-splash which would account for this slight increase of the readings of the VF over those of the GRG. For daily rainfall values of 6 mm and over the VF agrees with the GRG to within ± 1 per cent. The other noteworthy feature of these graphs is the large deficiencies shown by all the comparison gauges for small daily amounts. This seems to offer strong evidence that the flush gauges are still subject to exposure errors. Two major factors which contribute to loss of rain in rain-gauges are the wind speed and the raindrop-size; smaller drops will be affected more than larger drops by the wind. The problem is complex because there will be varying drop-sizes in a particular rainfall and here we are considering daily rainfall amounts which can be composed of entirely different types of rain at different times during the daily period. The shape of the curves in Figure 2 suggests that when the daily rainfall is small it is mainly composed of small drops and that, as is to be expected, if a big rainfall is recorded there has been a preponderance of large raindrops.

The scatter in Figure 1 probably largely reflects the variability of the size of the rain drops. A small anemometer (kindly loaned by Imperial College, London) was mounted at a height of 1 m above the ground about 4 m south of the TB gauge. The anemometer output was recorded on the same chart as that of the GRG, and the mean wind speed was evaluated for each daily rain measurement. The anemometer was out of action for some of the time so there are fewer observations of wind than of rain. The wind speeds were plotted against the ratio of the daily rainfalls measured by the GRG to those measured by the comparison gauges. There was considerable scatter with apparently little correlation between the ratio of the catches and the wind speed. The large scatter and small correlation has been noted by other experimenters.^{6,8} The results obtained in the present investigation are shown in Table IV as regression equations, with their 95 per cent confidence limits.

TABLE IV—REGRESSION EQUATIONS OF CATCH RATIO (Q) AGAINST WIND SPEED (m/s) AT A HEIGHT OF 1 METRE (U)

Gauge	Regression
A	$Q = 1.114 + 0.058 U \pm 0.20$
WMOF	$Q = 1.073 - 0.005 U \pm 0.13$
VF	$Q = 1.087 - 0.014 U \pm 0.16$
TB	$Q = 1.070 + 0.009 U \pm 0.24$

These equations are obtained from observations with a large scatter and in only a few of the observations was the wind speed less than 1 m/s. The catch ratio should be unity when there is no wind, so these equations only represent the relationship between the catch ratio and the wind speed when the latter is greater than 1 m/s. Whether it is significant that the two flush gauges show the catch ratio getting smaller with increasing wind can hardly be determined from this evidence. That there is not a marked increase in the catch ratio with increasing wind speed must be because the rainfalls with greater wind speeds are composed of larger drops which are not so readily deflected from the rain-gauges. Of course, the wind at the flush gauges will be less than that at the two gauges exposed at heights of 30 and 45 cm above the ground and the regression equations refer to the wind speed at a height of 1 m. On the assumption that the drop-size of rain is directly proportional to the rate of rainfall, an attempt was made to relate the catch ratio of gauges to the drop-size by plotting the catch ratio against the mean daily rate of rainfall. These rates of rainfall were estimated from the GRG record. In the course of a day the rate of rainfall could vary over a very large range and these mean rates of rainfall can only be rough estimates. Here again there was a very big scatter of the points plotted for all the gauges, but the regression lines through the points all showed a slight decline in the ratio of the catch of the GRG to that of the comparison gauge with increasing rate of rainfall.

It has not therefore been possible to isolate the losses in rain-gauge catch or to apportion these losses to the effect of wind speed or of drop-size. In practice few stations would be able to measure these other variables and a correction to the daily totals in a standard gauge as given by the regression equation in Table III would be all that could be attempted.

The whole analysis obviously needs to be tested over a longer period and at other stations where stronger winds are experienced and different weather

conditions prevail. The GRG recorded perfectly during both hail and snow but it was considered that since snow fell on only two days no useful conclusions could be drawn from these snowfalls. More investigations are needed of the measurements of very small rainfalls when evaporation and, in funnel gauges, adhesion of the rain to the gauges, are likely to be of greater significance. Further data may modify some of the conclusions suggested here but it is considered that enough evidence has been produced to show that the performance of the GRG is considerably better than that of the other gauges used in this comparison even when they are mounted flush with the ground.

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THE RELATIONSHIP BETWEEN MINIMUM TEMPERATURES OVER DIFFERENT GROUND SURFACES

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Summary. Minimum temperatures over concrete and bare-soil surfaces are examined in relation to the magnitude of the grass-minimum depression below the screen-minimum temperature. Regression equations, which enable the concrete and bare-soil minimum temperature to be forecast directly from the grass-minimum depression, are presented on a monthly and seasonal basis.

Introduction. The consequences of severe frost are of increasing economic importance, particularly to farmers, market gardeners and motorists. Accurate forecasts of the minimum temperatures over different ground surfaces are therefore even more essential now than they have been in the past.

The main factors which influence minimum temperatures near the surface of the ground are:

- (a) Outgoing radiation, which depends upon the nature and the temperature of the surface and also on the length of the cooling period.

- (b) Back radiation from the atmosphere, which depends on the height, amount and thickness of any cloud present, and also on the water-vapour content of the air.
- (c) Wind speed, which controls the depth of the mixing layer.

Other less important factors include the latent-heat exchange following any evaporation or condensation at the surface, and any conductive exchange of heat with adjacent layers of air or the ground.

These factors are taken into account in the standard methods of forecasting overnight minimum air temperatures due to Boyden,¹ McKenzie,² Saunders³ and others. Most outstations use a local refinement of one or other of these methods. Forecasts of the depression of the grass-minimum temperature below the screen-minimum temperature can be made by using other relationships found by Craddock and Pritchard⁴ and Saunders.⁵ More recently the interdependence between concrete and air-minimum temperatures (Parrey⁶ and Ritchie⁷) has been considered.

It is the intention of this note to consider the relationship between minimum temperatures recorded in the screen, and those over grass, concrete and bare-soil surfaces.

Data. Observations of the required minimum temperatures are recorded at Westbury-on-Trym (51°30'N, 2°37'W) near Bristol, from Monday to Friday each week. The period considered in this investigation was January 1972 to December 1973 which gave about 500 sets of observations. Minimum temperatures recorded during week-ends have been allocated to the night when the lowest air-minimum temperature as shown by the thermograph record occurred.

The concrete and bare-soil minimum thermometers were exposed horizontally with their bulbs in contact with the surface. The grass-minimum thermometer was exposed resting on two short pegs with the bulb just touching the tips of the grass, kept at about 2 cm long. The soil at Westbury-on-Trym is a clay-loam topsoil over a calcareous clay subsoil (Lower Lias). The bare plot was left undisturbed and kept free from weeds by using a total weed-killer. All thermometers were read and reset at 09 GMT in winter and at 08 GMT in summer. The surface thermometers were situated within 2 metres of each other, at a distance of 6 metres from the screen.

Analysis. The grass-minimum depression is forecast as routine at most stations and this analysis has therefore considered all minima in relation to the magnitude of the measured depression. Consequently the surface minima each night were expressed as follows:

- (a) Air-minimum minus grass-minimum temperature (G),
- (b) Concrete-minimum minus grass-minimum temperature (C) and
- (c) Bare-soil minimum minus grass-minimum temperature (S).

Grass-minimum depression (G). Craddock and Pritchard⁴ used data from 16 stations in their examination of this variable and showed that under favourable conditions a maximum value of 5 degC could be reached. Steele *et alii*⁸ present figures which suggest that the highest values for 10 stations in eastern England

reach 7 degC on very few occasions. Hogg,⁹ however, has shown that the maximum values for six places in south-west England ranged from 7 to 9 degC over a 10-year period, with one other station (Tavistock) recording a maximum depression of 11 degC.

The distribution of the grass-minimum depression at Westbury-on-Trym during the 2 years of this investigation is summarized in Table I, which also shows the frequency of the observations when the depression was at least 6.5 degC.

TABLE I—GRASS-MINIMUM DEPRESSION (*G*) AT WESTBURY-ON-TRYM, JANUARY 1972–DECEMBER 1973

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Mean (degC)	3.23	3.73	4.76	4.78	3.67	3.48	3.10	2.89	3.87	4.04	4.31	4.31	3.86*
Highest (degC)	7.8	8.1	8.8	7.1	6.9	7.5	6.5	6.7	6.3	7.3	7.8	7.3	8.8†
No. of obs.	43	40	43	38	41	43	43	44	38	45	44	36	498‡
No. of obs. ≥ 6.5 degC	5	7	14	9	2	3	1	1	0	2	9	3	56‡
Percentage of obs. ≥ 6.5 degC	12	17	33	24	5	7	2	2	0		20	8	11*
* Mean.	† Extreme.		‡ Total.										

These figures confirm that the maximum value of the grass-minimum depression in south-western England is greater than in eastern England. In all months except September, there was at least one night when the depression reached 6.5 degC, and in the important spring months, it is notable that the percentage of such nights was highest, reaching 33 per cent in March and 24 per cent in April.

Concrete-minimum temperature difference (C). The monthly distribution of the difference between the concrete and grass-minimum temperatures is given in Table II. To illustrate the occurrence of relatively large values of this variable, the frequency of nights when the magnitude was at least 2.5 degC is also shown.

TABLE II—CONCRETE-MINIMUM MINUS GRASS-MINIMUM TEMPERATURE DIFFERENCE (*C*) AT WESTBURY-ON-TRYM, JANUARY 1972–DECEMBER 1973

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Mean (degC)	1.14	1.46	2.03	2.47	2.09	2.04	1.96	1.71	2.30	2.16	1.96	1.69	1.92*
Highest (degC)	3.5	3.8	3.9	5.0	5.2	5.2	4.5	3.8	4.1	4.2	4.7	3.5	5.2†
No. of obs.													
≥ 2.5 degC	5	10	16	20	15	16	15	12	19	22	17	4	171‡
Percentage of obs. ≥ 2.5 degC	12	25	37	53	37	37	35	27	50	49	39	11	34*
* Mean.	† Extreme.		‡ Total.										

The frequency of the large values of (*C*) from November to March was lower than expected. There were 90 occasions of frost over concrete during this period and this confirmed the observation of Thornes¹⁰ who stated 'When the surface temperature falls to 0.0°C, the moisture both in and on the concrete begins to change state to ice; this takes place with the water at constant temperature around 0.0°C (depending on impurities, etc.) and any further fall of the surface temperature is delayed because of the release of latent heat as the water freezes'.

Again, there were fewer large values of S than expected during the winter months, and similar reasoning to that given for the concrete-minimum temperature applies. These results largely reflect those reported by Gloyne¹¹ who used a bare-soil minimum thermometer supported 0.5–1.0 cm above the soil. The seasonal analysis is given in Table V and the regression equations in Table VI.

TABLE V—RELATIONSHIP BETWEEN GRASS-MINIMUM DEPRESSION (G) AND BARE-SOIL MINIMUM MINUS GRASS-MINIMUM TEMPERATURE (S)

		Grass-minimum depression degC					
		<2.4	2.5–3.4	3.5–4.4	4.5–5.4	5.5–6.4	≥6.5
		Bare-soil minimum minus grass-minimum temperature					
Spring	Mean (degC)	0.64	1.34	1.96	2.66	3.43	3.51
(Mar.–May)	No. of obs.	27	17	11	19	23	25
	σ	0.46	0.55	0.58	0.57	0.55	0.67
Summer	Mean (degC)	0.78	1.49	1.66	2.81	3.26	4.62
(June–Aug.)	No. of obs.	54	22	12	26	11	5
	σ	0.53	0.71	0.86	0.57	0.63	0.72
Autumn	Mean (degC)	0.39	1.31	2.11	2.60	2.92	3.53
(Sept.–Nov.)	No. of obs.	28	17	19	23	29	11
	σ	0.63	0.53	0.66	0.80	0.52	1.04
Winter	Mean (degC)	0.36	1.15	1.74	2.49	2.96	4.71
(Dec.–Feb.)	No. of obs.	33	19	23	15	14	15
	σ	0.50	0.54	0.54	0.84	1.25	1.26
Year	Mean (degC)	0.58	1.34	1.87	2.66	3.13	3.94
	No. of obs.	142	75	65	83	77	56
	σ	0.56	0.62	0.66	0.69	0.75	1.08

σ = standard deviation of the observations.

Regression equations have been derived on a monthly and seasonal basis and these are given in Table VI together with their correlation coefficients. These enable estimates of the minimum temperature over concrete and over bare soil to be made directly from the grass-minimum depression.

Conclusions. Under favourable conditions, the grass-minimum depression at Westbury-on-Trym frequently exceeds 7 degC, and can reach 9 degC on a few nights in spring.

Seasonal and annual relationships have been established between the magnitude of the grass-minimum depression and the differences between (a) the concrete and grass minima and (b) the bare-soil and grass minima. These differences all show high correlation with the grass-minimum depression and it is suggested that they can be used to forecast the minimum temperature over each surface directly from the grass-minimum depression, which is now forecast as routine at most stations.

It is stressed, however, that these results have been derived at one place in south-west England, and that elsewhere they should be used with some caution. Further, it is suggested that thermometer bulbs just touching the surface might be giving values slightly less than those of the surface itself (perhaps by about 0.5 degC) so that freezing of the surface does not occur until after the reading of the thermometer has fallen a little below 0°C.

TABLE VI—MINIMUM TEMPERATURES OVER DIFFERENT SURFACES—REGRESSION EQUATIONS

	Concrete-minimum minus grass-minimum temperature difference		Bare-soil minimum minus grass-minimum temperature difference	
	Regression equations <i>G</i>	Correlation coefficients <i>r</i>	Regression equations <i>S</i>	Correlation coefficients <i>r</i>
January*	0.35 <i>G</i>	0.92	0.67 <i>G</i> - 0.29	0.88
February	0.42 <i>G</i> - 0.11	0.83	0.64 <i>G</i> - 0.49	0.88
March	0.42 <i>G</i> + 0.03	0.86	0.53 <i>G</i> - 0.14	0.87
April*	0.48 <i>G</i> + 0.17	0.81	0.52 <i>G</i> - 0.09	0.92
May	0.58 <i>G</i> - 0.11	0.85	0.60 <i>G</i> - 0.17	0.94
June	0.55 <i>G</i> + 0.12	0.87	0.58 <i>G</i> + 0.08	0.91
July*	0.55 <i>G</i> + 0.25	0.88	0.53 <i>G</i> + 0.16	0.83
August	0.47 <i>G</i> + 0.34	0.83	0.49 <i>G</i> - 0.05	0.80
September	0.46 <i>G</i> + 0.54	0.86	0.51 <i>G</i> + 0.20	0.86
October*	0.49 <i>G</i> + 0.20	0.86	0.51 <i>G</i> - 0.04	0.86
November	0.44 <i>G</i> - 0.03	0.82	0.61 <i>G</i> - 0.61	0.88
December	0.37 <i>G</i> + 0.11	0.75	0.56 <i>G</i> - 0.57	0.78
Spring	0.47 <i>G</i> + 0.13	0.84	0.54 <i>G</i> - 0.08	0.90
Summer	0.53 <i>G</i> + 0.24	0.86	0.55 <i>G</i> + 0.01	0.85
Autumn	0.44 <i>G</i> + 0.29	0.82	0.53 <i>G</i> - 0.17	0.86
Winter	0.39 <i>G</i> - 0.03	0.85	0.62 <i>G</i> - 0.43	0.85
Year	0.45 <i>G</i> + 0.20	0.82	0.55 <i>G</i> - 0.14	0.86

G concrete-minimum minus grass-minimum temperature

S bare-soil minimum minus grass-minimum temperature

G grass-minimum depression

* The relationships in the months indicated are shown in Figures 1 and 2 overleaf.

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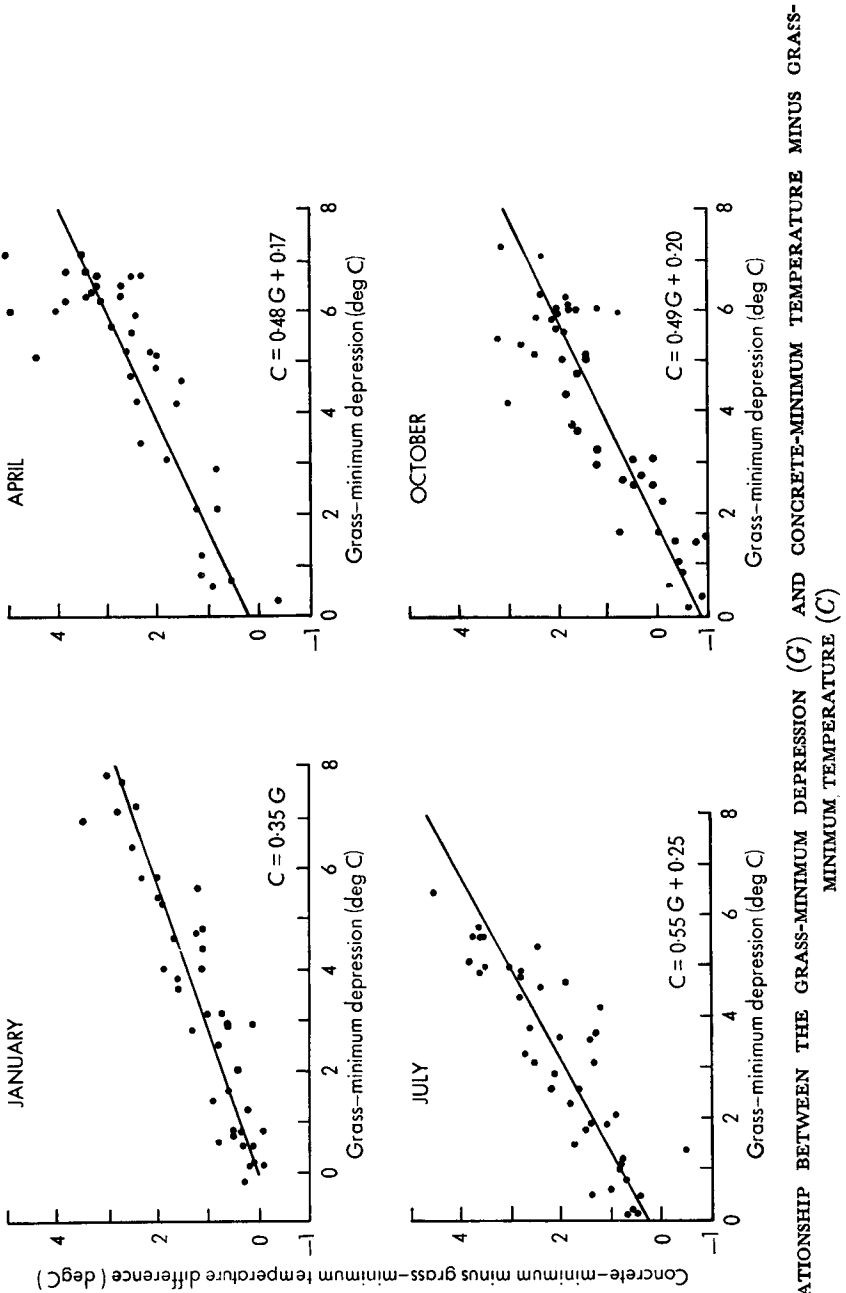


FIGURE 1—RELATIONSHIP BETWEEN THE GRASS-MINIMUM DEPRESSION (G) AND CONCRETE-MINIMUM TEMPERATURE MINUS GRASS-MINIMUM TEMPERATURE (C)

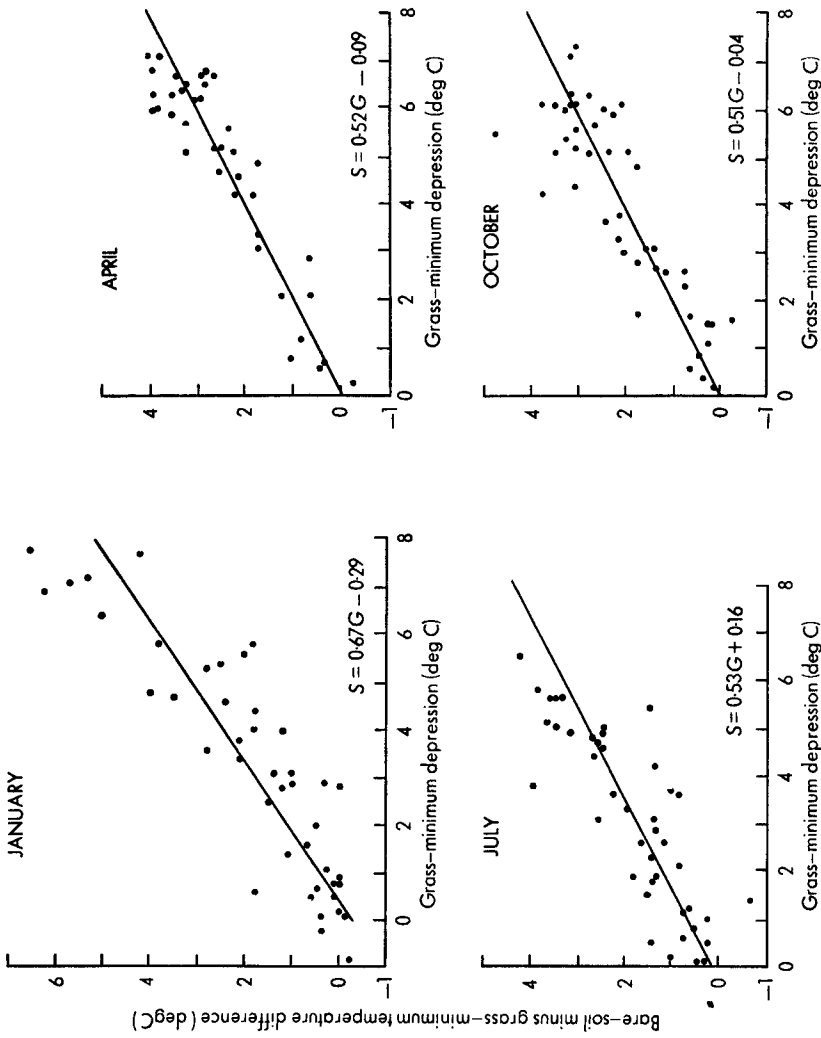


FIGURE 2—RELATIONSHIP BETWEEN THE GRASS-MINIMUM DEPRESSION (G) AND BARE-SOIL MINIMUM TEMPERATURE MINUS GRASS-MINIMUM TEMPERATURE (S)

REVIEWS

World climatology—an environmental approach, by J. G. Lockwood. 250 mm × 180 mm, pp. xiv + 330, *illus.*, Edward Arnold (Publishers) Ltd, 25 Hill Street, London, W1X 8LL, 1974. Price: £8.50.

The recent quickening of interest in Man's natural environment has come at a time when new methods of observation and analysis have brought great advances in knowledge of global climatology and deepened understanding of the processes by which climate is generated and which cause it to vary with time. The text here reviewed is of moderate length, lavishly illustrated by a large number of maps and diagrams, some of which explain the workings of climate, while many others contribute to a great variety of practical applications. It was time to write a new text, and this one may serve as a modern companion to Kendrew's well-known works. It provides an English-language text with many of the virtues of Dr Joachim Blüthgen's *Allgemeine Klimageographie* (published in Berlin by Walter de Gruyter & Co., 2nd edition 1966).

Lockwood's book is very much its author's child, admirable on the topics that have interested him and fairly comprehensive on fundamentals, but patchy when it comes to regional coverage. There is much on south Asia and on equatorial climates, particularly in the Malaysian-Indonesian sector, much less on east Africa and hardly anything on South America. Nevertheless, the short chapter (11 pages) on polar climates is good. Climatic change and the variability of conditions from year to year do not appear in the index at all (though there are a few items on year-to-year variations in the text). Mathematical expressions are used, where appropriate, to define concepts and relationships, but there are no mathematical derivations. The author's concern about definitions has led to the inclusion of a useful short glossary; a number of concepts, however, are only barely defined, not expounded in any way devised to help those readers to whom the field is new. Apart from this criticism, the text and especially the diagrams struck the reviewer as admirably clear. The author has the true geographer's facility for portraying processes in three dimensions. A particularly nice trio of diagrams (on page 196) makes clear why showers reach their maximum in the evening on the east coast of Malaya. The extreme clarity of the maps has, however, generally been attained at the cost of omitting the latitude and longitude net altogether.

Many of the pictures are outstanding choices, and they illustrate a wide range of environmental conditions from icing on ships in polar waters, and tornadoes and lightning flashes, to a good selection of satellite and aircraft photographs of cloud systems in various parts of the world.

The book has been written with the interests of agriculturists, botanists, civil engineers, geographers and meteorologists, and university students in these subjects, in mind. This has clearly guided the choice of matter for tables and diagrams, which include a variety of data on evapotranspiration, soil moisture, soil temperatures, water balance, streamline diagrams, albedo maps etc. The world map (page 42) of mean annual albedo, derived from satellite measurements, is interesting because it manifestly does not support the latest, often quoted, estimates of 30 per cent or less for the global average albedo. Other points of interest in the book include a rather good global survey of the incidence of tropical storms (though without explaining the absence of these storms in the

South Atlantic), an account of the occurrence of frosts in Java (from observations in the tea estates at the higher levels), and a likening of the change of wind with height in the free air to the corresponding Ekman spiral in the current movements in the upper layers of the ocean.

The author has written in a way that will stimulate many in their quest for deeper knowledge and understanding. As he states in the preface, 'most climatological text books concentrate on the mathematics and physics of the atmosphere and neglect the environment created by the atmosphere'. As the statement implies, they also generally neglect the seas which cover 70 per cent of the earth and the processes in the seas that affect the atmosphere. This book does not contain a lot about the ocean, but the subject is not neglected: the book does, for instance, present Tucker's revision of the usual ideas of distribution of precipitation over the ocean. Unfortunately the startling nature of Tucker's result is not stressed, nor the fact that it seems to have been largely disregarded in most estimates of the total global precipitation and its distribution.

This is a useful book, and a nice book, that will encourage pursuit of the subject, but it is not a fully comprehensive or encyclopaedic text such as the climatologies of Kendrew or the German texts from Hann to Blüthgen. It is a modern supplement to the older works, which no library covering applied climatology can afford to be without, and which those individuals who can afford it will find attractive and widely informative.

H. H. LAMB

The physics of mesospheric (noctilucent) clouds, edited by J. Ikaunieks. 245 mm × 170 mm, pp. viii + 156 (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), John Wiley & Sons Ltd, Baffins Lane, Chichester, Sussex, 1974. Price: £7.50.

The book is another of the excellent translations from the Israel Program for Scientific Translations whose standard is kept at a high, though not always truly idiomatic, level. The original Russian text was published in Riga in 1970 and is an assembly of 22 of 30 papers originally presented at the 1968 Riga Conference on Mesospheric Clouds. All the papers at this conference are by authors from the U.S.S.R., which is perhaps natural because—until recent years—studies of noctilucent clouds have, in the main, been made in the U.S.S.R. Although the papers are now six years old, the development of the subject has not been as rapid as that in other areas of mesospheric studies and much of the research reported in the book has not been overtaken by events or become of only historical interest.

Many of the papers deal with the possible influence of solar activity upon the occurrence of noctilucent clouds, with the keynote sounded by a review of the Megrelishvili and Khvostikov concept of terrestrial accretion of hydrogen from the solar wind to give 'solar rain' in the mesosphere. The experimental data—mainly statistical analyses for a 10- or 11-year periodicity—retain their interest but the theoretical models are almost certainly open to criticism in the light of present ideas. The most convincing analysis is possibly that reported by Vasil'ev, who demonstrates a correlation between the rate of occurrence of noctilucent clouds and both the sunspot number and a four-year cycle in the difference between the monthly means in the January and the February tropospheric temperatures.

For researchers interested in the subject of airglow—the emission of light from the upper atmosphere—there is an important paper by Toroshelidze in which he reports an extensive series of twilight measurements of the hydroxyl emission at $1.08\text{-}\mu\text{m}$ wavelength. Vasil'ev and Fast present an interesting discussion of the optical effects seen in the atmosphere during the summer of 1908 after the fall of the Tunguska meteorite, particularly mentioning the curious 'bright nights' that were remarked at the time. Bronshten's review of the history of the discovery and early investigations of noctilucent clouds contains much that was new to this reviewer.

In summary, this book is like so many conference proceedings: many years have gone by since the papers were originally presented, there is no single thread of development through the book and the contributions differ considerably in level of treatment. However, given the particular character of noctilucent cloud studies, these proceedings survive well and can be recommended to be on a bookshelf available to any aeronomer or meteorologist.

M. GADSDEN

Climatology from satellites, by E. C. Barrett. 240 mm \times 155 mm, pp. xii + 418, illus., Methuen and Co. Ltd, 11 New Fetter Lane, London EC4P 4EE, 1974. Price: £7.90. (Also distributed in the U.S.A. by Harper and Row Publishers, Inc., Barnes and Noble Import Division, New York.)

Every meteorologist seems to have his own personal definition of the term 'climatology', so perhaps the scope of this book is not immediately clear from its title. However, at the outset, Dr Barrett defines the various subdivisions of the subject and identifies those which can be profitably pursued by making use of data from meteorological satellites. Because of the ease of access to the American literature, the author concentrates throughout on the U.S. systems, and, in an early chapter, summarizes the characteristics of the various satellites in operation since TIROS I was launched on 1 April 1960. The general problems associated with orbits, sensors and data acquisition, processing and presentation, are also briefly covered in this chapter.

The next two sections, of three chapters each, are devoted to 'Principles of weather satellite data analysis' and 'Satellite data analyses in global climatology'. This distinction is not altogether successful since in the first of these sections the principles obviously need to be illustrated with examples, which tend to overlap and duplicate the coverage given in the second section. Separate chapters are devoted to (radiative) energy, moisture (including cloud cover and rainfall) and circulation patterns.

The largest section in the book covers the use of satellite data in studies of regional climatology. The tropics (two chapters), the south Asian monsoon area, the baroclinic mid latitudes and the polar regions are all given detailed treatment, with greatest emphasis being laid on those aspects which have benefited most from the study of satellite data.

The final chapter, on the classification of climates, briefly covers the drawbacks of existing methods of classifying climate on global and regional scales (basically Köppen and modifications) and goes on to suggest an approach to classification more related to meteorological first principles. It is proposed that net radiation, relative vorticity and the precipitation/evaporation balance be

used as 'yes/no' or 'positive/negative' discriminators to define climatic regions, and with recent advances in data acquisition on a global scale, it is argued that this approach is now becoming feasible.

Throughout, this book is extremely readable, smoothly relating climatological concepts (both established and emerging) to the new forms of data now available. Satellite jargon is kept to an acceptable minimum, the bibliography is extensive and up to date and typographical errors are few. Diagrams are clear and the (black-and-white) photographs show many examples of how processed data may be presented.

All in all, this is a book to be recommended as a modern view of global climatology and also as a summary of the practical achievements of meteorological-satellite technology over the last decade.

J. S. HOPKINS

PUBLICATIONS RECEIVED

The following have been received from the Meteorological Institute of the University of Thessaloniki:

Climatologica 4: *The etesian winds: proof of the stability of the climate of Greece.*

By G. C. Livadas. 1974. (In Greek.)

Meteorologica 33: *Sequences of rain and drought in Thessaloniki (II).* By V. E. Angouridakis. 1973.

Meteorologica 34: *On a certain effect of mountain masses on aerial photography.* By E. N. Patmios and G. C. Livadas. 1973.

Meteorologica 35: *Wind in Thessaloniki—Greece.* By G. C. Livadas and Char. S. Sahsamanoğlu. 1973.

Université de Thessaloniki. *Annuaire de l'Institut Météorologique et Climatologique*, 42. *Observations Météorologiques de Thessaloniki 1973*, publiées par le Prof. Dr. G. C. Livadas, Thessaloniki, 1974.

NOTES AND NEWS

The Atlantic Tropical Experiment of the Global Atmospheric Research Programme

The operational phase of the Atlantic Tropical Experiment of the Global Atmospheric Research Programme (GATE) has now been completed. Important contributions to this major international project were made by teams from the United Kingdom on two small chartered ships, H.M. Survey Ship *Hecla* and the C-130 aircraft of the Meteorological Research Flight. This aircraft logged 336 hours in 40 operational missions with almost no faults either in its own performance or in the instruments carried. Most of the flights were made at low level in order to measure fluxes of heat, water vapour and momentum, the aircraft being one of only three that were equipped to do this. The aircraft was one of the most versatile taking part in GATE and was used by the Airborne Mission Scientist as lead aircraft on 17 occasions. In Phase 3 it was struck by lightning which destroyed one of the wind vanes.

Climatological Atlas of the United Kingdom

The preparation by the Meteorological Office of a Climatological Atlas of the British Isles based largely on data covering the period 1901–30 was begun in 1938 but had to be suspended at the outbreak of the Second World War. Work was resumed in 1945 and the Atlas was eventually published by H.M. Stationery Office in 1952. This edition went out of print in 1966.

Work on a new atlas covering the United Kingdom for the period 1941–70 was started in 1972 and is well advanced. However, it has become apparent that this atlas cannot be marketed unless it is heavily subsidized. Reluctantly the Meteorological Office has had to take the decision not to subsidize and therefore not to publish it.

It is intended that separate sections each dealing with a particular element will be prepared and published in a cheaper form. A start has been made with barometric pressure and *Climatological Memorandum* No. 51A can now be obtained from the Meteorological Office, price £3.50. This Memorandum contains monthly and annual mean-sea-level pressure maps for 09 GMT for the United Kingdom for the period 1941–70, and some additional statistics. It is hoped to have further sections available soon: sunshine maps by the end of 1974, maps showing the number of days with snow falling and snow lying and of gales early in 1975, and a memorandum on temperature by mid 1975. Humidity maps will be available later. The prices of these publications have yet to be determined.

The display of climatological data in an atlas must of necessity be rather stereotyped and generalized and cannot meet all the requirements of many practical users. For them the Meteorological Office can usually undertake to process and present climatological data in a way which is suited to a client's particular needs, for a fee depending on the staff and computer time taken up.

New Joint Financing Agreement on North Atlantic Ocean Stations

A new Joint Financing Agreement on North Atlantic Ocean Stations (NAOS) has been concluded in Geneva by the Conference of Plenipotentiary Delegations convened at WMO Headquarters by Dr D. A. Davies, Secretary-General of WMO. The Conference, which was sponsored by WMO and the International Civil Aviation Organization, first met from 18 February to 1 March and then from 4 to 15 November 1974 under the chairmanship of Mr Raymond Schneider, Director of the Swiss Meteorological Institute and Permanent Representative of Switzerland with WMO.

The new Agreement will operate under the auspices of WMO, and will ensure the joint operation and financing of a network of four ocean stations in the North Atlantic primarily for meteorological purposes. This Agreement will in fact replace as from 1 July 1975 an existing Agreement concluded in 1948 under the auspices of the International Civil Aviation Organization which organized the NAOS network for the primary purpose of providing adequate air navigation facilities over the North Atlantic. In adopting the new Agreement the Conference recognized that the NAOS network is essential for weather forecasting in the northern hemisphere.

The four stations are located in the central and eastern parts of the North Atlantic and each of them will be permanently occupied by a vessel specially equipped and staffed to carry out surface and upper-air meteorological observations plus a number of secondary services including retransmission of weather reports, safety services to other ships and aircraft and oceanographic observations. The stations will be operated by the U.S.S.R. (Station C (52°45'N, 35°30'W)), the United Kingdom (Station L (57°N, 20°W)), the Netherlands, Norway and Sweden (Station M (66°N, 02°E)) and France (Station R (47°N, 17°W)). Two or three ocean-going vessels are required for the regular operation of each station. The unit of account will be the pound sterling and it is estimated that for the first financial period, i.e. 1 July 1975 to 31 December 1976, the average operating cost will be about £1 000 000 per station.

The financial basis of the Agreement is that, while the countries mentioned above will operate the network of NAOS stations, the other signatory countries will make financial contributions to the cost of the operations. The initial duration of the Agreement will be until 31 December 1981; it may thereafter be extended from year to year. A Board on which all participating countries will be represented has been established to supervise the operation of the Agreement, which will be administered by WMO.

The Secretary-General of WMO presided over the signing ceremony which took place at WMO Headquarters on 15 November 1974. The Agreement will remain open for signature until 31 May 1975.

WMO PRESS RELEASE

Retirement of Mr P. F. Illsley

Mr P. F. Illsley joined the Meteorological Office as a Technical Officer in 1937 after graduating from the University of Nottingham with a first-class honours degree in Physics. Following training at Croydon he was soon engaged in forecasting duties for aviation. During the first part of the Second World War he had many postings in this country which included short spells at several RAF Group Headquarters and Prestwick, and a rather longer one at Dunstable. Later he joined the Royal Air Force Volunteer Reserve (Meteorological Branch) and served in North Africa. On release from the RAFVR in January 1946 Mr Illsley again served for short spells at several RAF stations which were closing. He then served for two years at Gibraltar.

On his return to the United Kingdom in 1948 he was promoted to Principal Scientific Officer and served for a normal tour of duty as Senior Meteorological Officer, Plymouth. This was followed by eight years on the Senior Forecasters' Bench at the Central Forecasting Office, Dunstable from 1952 to 1960. Subsequently he served as Chief Meteorological Officer at Headquarters RAF Germany from 1961 to 1964 and at Headquarters Coastal Command from 1964 to 1972.

He was promoted to Senior Principal Scientific Officer and moved to Bracknell in 1972 in order to head the Climatological Services Branch in which he stayed until his retirement on 31 January 1975.

I have known him since the pre-war days at Croydon in April 1937. Throughout his career, which has been almost entirely concerned with meteorological services, Mr Illsley has displayed a very forthright approach to his work. Those of us who had occasion to discuss the current meteorological situation or forecast with him soon appreciated that forthright—sometimes somewhat blunt—expression of his views, which were usually based on a very keen perception and understanding of the situation and shrewd assessments of the likely developments. To telephone him at CFO for a discussion of the meteorological situation was always a refreshing and beneficial experience and usually—but not always—comforting. He brought the same refreshing direct approach to his work as Head of the Climatological Services Branch and has maintained it during his four years at Bracknell. With his retirement the Meteorological Office will miss his long and broad experience in practical meteorological matters.

Mr and Mrs Illsley are retiring to Church Stretton, Shropshire. Their many friends and colleagues in the Meteorological Office will, I am sure, wish them both a long and happy future.

N. BRADBURY

AWARD

Dr Raymond Hide, F.R.S.; Head of the Geophysical Fluid Dynamics Laboratory, Meteorological Office, Bracknell, has been awarded the Charles Chree Medal and Prize for 1975 by the Institute of Physics, in recognition of 'his contributions, both experimental and theoretical, to the hydrodynamics of rotating fluids and its application to the understanding of motions in the atmospheres and interiors of the major planets'.

OBITUARY

It is with regret that we have to record the death of Mr J. J. Trainor, Assistant Scientific Officer, on 14 November 1974 while in approved employment in Australia.

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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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THE METEOROLOGICAL MAGAZINE

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PROFESSOR SVERRE PETTERSSSEN, C.B.E.

With the passing of Professor Sverre Petterssen at his London home on 31 December, international meteorology lost one of its outstanding figures.

Born in Norway in 1898, Petterssen graduated at Oslo University in 1924, took his Ph.D. in 1933, and served in the Norwegian Meteorological Service from 1924 to 1939, during the last eight years as a regional director. In 1939 he left Norway to become Professor of Meteorology at the Massachusetts Institute of Technology but, in 1942, came to England as a Lieutenant Colonel in the Norwegian Air Force and served for the rest of the war in the Meteorological Office at Dunstable where he established techniques of upper-air analysis which have since become standard throughout the world. As a senior member of the team responsible for producing the weather forecasts for the D-Day landings in Normandy, he received a letter of commendation from General Eisenhower. His services to the war effort were further recognized when he was appointed C.B.E. in 1948, and Commander of the Order of St Olaf by the Norwegian Government in 1949.

While serving with the Norwegian Meteorological Service, Petterssen made many highly original contributions to the theory of frontogenesis and convection, to the kinematics of weather systems, to the theory of development of the pressure field and to the physics of fog. In all his work he saw the problem from the forecaster's point of view, and although he sought to elucidate the fundamentals of the problem, he presented his results in a manner which could always be readily applied to forecasting. The textbook which he published in 1940 was the first book to attempt to deal with the forecasters' problems in an organized and quantitative way. Earlier textbooks had either been purely descriptive, or had treated meteorology as a largely academic discipline in which the forecaster had to find his own applications of the theoretical results if he could. Petterssen's book came at an opportune time when the Allied Meteorological Services were expanding rapidly to meet the requirements of the Second World War, and his influence on British forecasting practice was made more penetrating by a number of unpublished memoranda on technical problems which he wrote for distribution to forecasters. Several generations of students were brought up on successive editions of his *Introduction to meteorology* which was translated into Russian, Polish and Hindustani and which probably sold more copies than any other meteorological textbook.

In 1945 Petterssen returned to Norway and served as Chief of the Norwegian Weather Forecasting Service until 1948 when he was appointed Director of Scientific Services of the United States Air Force Weather Service. In 1952

he returned to academic life as Professor of Meteorology in the University of Chicago and served as Chairman of the department from 1960 to 1963. During this decade Petterssen played a major part in the rapid expansion of meteorological research and education in the United States within both government and academic institutions. His interest in synoptic and forecasting problems did not diminish and the research which he carried out or initiated among his students and fellow workers continued to emphasize the analysis and interpretation of the real atmosphere at a time when theoretical and mathematical treatments were in vogue.

These major achievements were recognized by the award of the Symons Gold Medal, the highest award of the Royal Meteorological Society, in 1969, the Buys Ballot Gold Medal (awarded only once in a decade) by the Netherlands Academy of Sciences and several honours by the American Meteorological Society of which he was president in 1958-59. His great meteorological knowledge and wisdom were in great demand in the councils of the International Meteorological Organization where he served as president of the Commission for Maritime Meteorology (1939-46) and of the International Aerological Commission (1946-50). In 1965 the World Meteorological Organization awarded him its greatest honour, the IMO Gold Medal and Prize.

After retirement from the University in 1963, Professor Petterssen spent two happy years as U.S. Science Attaché to the Scandinavian countries, having been a United States citizen from 1955 until he relinquished this citizenship in 1974. He chose to spend his final years with his English wife Grace in London, where he continued to write until the day of his death. In his autobiographical 'Kuling fra Nord', which has just appeared in Norwegian, he sums up the experiences and philosophy of an extremely active, exciting and fruitful life.

His colleagues and friends will greatly miss a remarkable and lovable man who made a profound and lasting impression on meteorology which continued to excite him to the very end.

B. J. MASON

J. S. SAWYER

551.524.36

EXTREME TEMPERATURES OVER THE UNITED KINGDOM FOR DESIGN PURPOSES

By J. S. HOPKINS and K. W. WHYTE

Summary. Extreme maximum and minimum temperatures at a network of over 200 stations over the United Kingdom have been analysed, and maps of once-in-50-year extreme temperatures prepared. A correction diagram is also presented which enables estimates for other return periods to be made.

Introduction. For a number of engineering design applications a knowledge of extreme high or low air temperatures which may be attained is important. For example, certain steels used in the construction of masts, pylons and the like are subject to brittle fracture at low temperatures. In general, steels with guaranteed ductility at low temperatures are more

expensive, and so the designer is interested in identifying areas where low temperatures frequently occur so that the best decision can be made on the type of steel to be used for a particular job.

Bridges are sensitive to extreme temperatures at both ends of the scale, and so allowance must be made at the design stage for the safe expansion and contraction of the deck. A recent draft Code of Practice¹ has specified that the once-in-120-year extreme temperatures should be used in the design of the main structural elements in bridges and once-in-20-year extremes used where non-structural equipment is being considered.

Thus, as with the problems of wind loading of structures, a simple statement of the extreme value recorded at a climatological station in the area is not sufficiently statistically precise for modern design methods. A study of the statistics of extremes is needed, so that the designer may make his decisions regarding cost and safety on as sound a basis as possible.

Methods of analysis. The estimation of the extreme values to be expected at low probabilities is normally accomplished by assigning to the ordered set of n available annual extremes x_m ($m = 1, 2, \dots, n$) some convenient cumulative probabilities p_m (such as $p_m = m/(n + 1)$ or preferably $p_m = (m - 0.31)/(n + 0.38)$), and then fitting a straight line

$$x = x_0 + \alpha y, \quad \dots \quad (1)$$

where the 'reduced variate' $y = -\log_e (-\log_e p)$, and x_0 and α are parameters to be determined. Defining the return period T as $\frac{1}{1-p}$, the once-in- T -years

extreme value is then the value x given by (1) for $y = -\log_e (-\log_e (1 - \frac{1}{T}))$.

This is the approach popularized by Gumbel.²

Jenkinson³ showed that the straight line (1) is the special two-parameter case of the more general three-parameter distribution

$$x = x_0 + \alpha \left(\frac{1 - e^{-ky}}{k} \right) \quad \dots \quad (2)$$

when the curvature parameter k is zero, and he devised a computational scheme⁴ for determining the maximum-likelihood solution for the parameters in both (1) and (2).

Jenkinson has also suggested that it may be appropriate to weight the members of a set of annual extremes so as to simulate a set of five-year extremes and ensure that any extrapolation is based on the upper (lower) part of the distribution of annual maxima (minima).

The various maximum-likelihood solutions for the different methods are shown in Figure 1 for the particular example of annual maximum temperatures at Oxford for the period 1853-1972.

It might be thought that the three-parameter solution with positive k giving the upper limit $x_0 + \alpha/k$ would be the most appropriate distribution to choose, since on physical grounds it cannot reasonably be expected that maximum temperatures will increase without limit. However, in the analysis of the various series of annual extreme temperatures it was found that the three-parameter maximum-likelihood solution often gave unrealistically low values for the upper limit in both the weighted and unweighted cases. Typically,

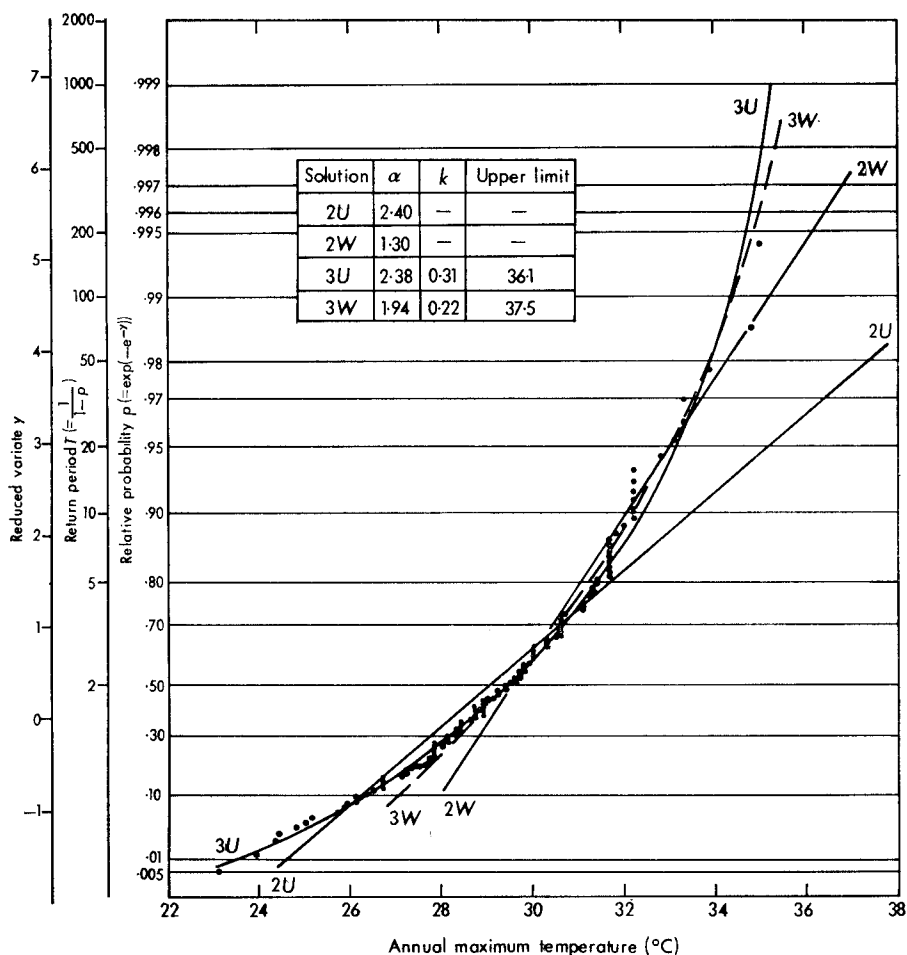


FIGURE 1—EXTREME-VALUE ANALYSIS OF ANNUAL MAXIMUM TEMPERATURES AT OXFORD (1853-1972)

Each point (·) represents one annual maximum temperature, plotted according to the

$$\text{scheme } p_m = \frac{m - 0.31}{120 + 0.38},$$

where m is the rank (= 1, 2, ..., 120).

The four solutions obtained by maximum-likelihood methods are:

- 2 U — the 2-parameter unweighted solution,
- 2 W — the 2-parameter weighted solution,
- 3 U — the 3-parameter unweighted solution, and
- 3 W — the 3-parameter weighted solution.

Note. The right-hand y-axis label should read 'Cumulative probability ...'

values of k were about 0.5 and this exaggerated curvature meant that the limiting value was little different from the most extreme observed temperature. Though this problem occurred more frequently with maximum temperatures it also arose with the minimum-temperature analysis at several stations. With minima, however, it was more usual to obtain smaller positive or even occasionally negative values of k .

For design purposes, it is obviously better for an estimate to err on the 'safe' side, and the two-parameter weighted solution does tend to give slightly higher maxima and lower minima at a return period of 50 years than do the three-parameter solutions. It is therefore considered that for both maximum and minimum temperatures the two-parameter method with five-year weighting (being effectively a straight-line extrapolation of the upper (lower) part of the observed distribution) gives the most satisfactory estimates of the extreme temperatures corresponding to return periods of the order of 100 years. Clearly for longer return periods, any estimates of extreme temperatures based on a comparatively short period of record might be unreliable because of long-term climatic fluctuations.

Data available and choice of period. The choice of basic data for this analysis was dictated by the fact that extreme temperatures for the period 1941-70 were readily available on magnetic tape for 219 stations in the United Kingdom, of which 121 had values for the full 30 years and the remainder had values for at least 20 years. Ideally, we would wish the 1941-70 extremes to be representative of the *next* few decades, since the computed extremes will be used for planning structures which will be exposed to air temperatures over that future period. However, if it can be shown that the chosen 30-year period yields extreme-value estimates which agree with those derived from longer periods of record, then the choice of 1941-70 can be accepted with reasonable confidence.

Fifty-year return-period values of maximum and minimum temperatures were calculated for 15 long-period stations whose data had been collated (sometimes by combining different sites from the same town) by the Synoptic Climatology Branch of the Meteorological Office. The results obtained by using both the full available period of record and the 1941-70 period are shown in Table I. At almost all stations, the once-in-50-year minimum temperature derived from 1941-70 data is higher than that derived from the full period of record, and especially so at sites within large urban areas such as Bradford, Kew, Oxford and Sheffield. This would suggest that for estimation of minima, the latest period of data, reflecting current urban influences, forms the most suitable basis for design purposes. (However, see the later discussion on mapping of urban minima.) There is no such systematic difference between 50-year maxima, maximum positive and negative differences of the order of 1 degC being found. This suggests that the 1941-70 period has experienced a sample of extreme maximum temperatures which is reasonably representative, over the country as a whole, of a 'typical' 30-year period, and so extreme-value estimates based on this period are likely to be acceptable for design purposes.

TABLE 1—COMPARISON OF ESTIMATES OF ONCE-IN-50-YEAR TEMPERATURES ($^{\circ}\text{C}$) AT SELECTED STATIONS BASED ON FULL AVAILABLE RECORD AND ON PERIOD 1941–70

	Once-in-50-year temperatures (°C) estimated from:						
	No. of years in full period (Max./Min.)	A Full period		B 1941-70		B - A (degC)	
		Max.	Min.	Max.	Min.	Max.	Min.
Armagh	108/107	30.0	-13.7	30.0	-13.0	0.0	+0.7
Bradford	65	31.6	-14.0	31.8	-13.1	+0.2	+0.9
Bidston	102	31.8	-11.6	31.6	-9.6	-0.2	+2.0
Cambridge (Botanic Gardens)	40/42	35.5	-16.1	34.8	-16.7	-0.7	-0.6
Cardiff	60	32.3	-13.9	32.0	-13.2	-0.3	+0.7
Durham	42	32.5	-16.3	31.4	-15.6	-1.1	+0.7
Edgbaston	42/43	33.0	-11.3	32.8	-10.9	-0.2	+0.4
Edinburgh (Blackford Hill)	77	30.2	-10.1	30.0	-10.2	-0.2	-0.1
Hastings	41/42	32.4	-9.7	32.8	-9.1	+0.4	+0.6
Kew (North Wall screen)	92	34.6	-12.3	35.6	-10.0	+1.0	+2.3
Nottingham	49	33.6	-13.4	33.6	-13.3	0.0	+0.1
Oxford	120	34.3	-15.8	34.2	-14.3	-0.1	+1.5
Plymouth	99	30.7	-8.8	31.0	-9.1	+0.3	-0.3
Sheffield	89/90	33.1	-12.0	33.2	-10.3	+0.1	+1.7
Southampton	110/107	33.8	-12.1	34.9	-11.2	+1.1	+0.9
Mean differences						+0.02	+0.77

Preparation of maps. Figures 2 and 3 are based on once-in-50-years extreme temperatures calculated by the weighted two-parameter method for each station in the 1941–70 network. The aim in mapping the results of the extreme-value computations was to show the broad-scale pattern resulting from the maritime influence, or lack of it, on extreme temperatures. In order to enable a reasonably smooth pattern to be drawn on a relatively small-scale map (the working chart was $1:2 \times 10^6$), reduction of the plotted values to a common datum level was necessary. Comparison of data from the few available high-level stations with nearby low-level sites indicated that 0.5 and 1.0 degC/100 m seemed reasonable altitude correction factors for the reduction to mean sea level of extreme minimum and maximum temperatures, respectively. When adjusted by these factors, the plotted values generally proved easy to analyse, and gave patterns which were physically realistic.

With the maximum temperatures, very few plotted values (adjusted for altitude) departed by more than 1 degC or so from the final analysed isopleth pattern. With minimum temperatures, there were many more such departures at urban sites and at low-lying sheltered sites having higher and lower minima respectively than at nearby open country sites. The map of once-in-50-year minima has therefore been analysed with little weight being given to estimates at sites in frost hollows and urban areas. Observations in the London area, however, have been analysed, since the considerable spatial extent of the conurbation can be represented on a small-scale map and there are sufficient stations available to define the pattern over and around London. Apart from in and around London therefore, the map (Figure 2) describes conditions to

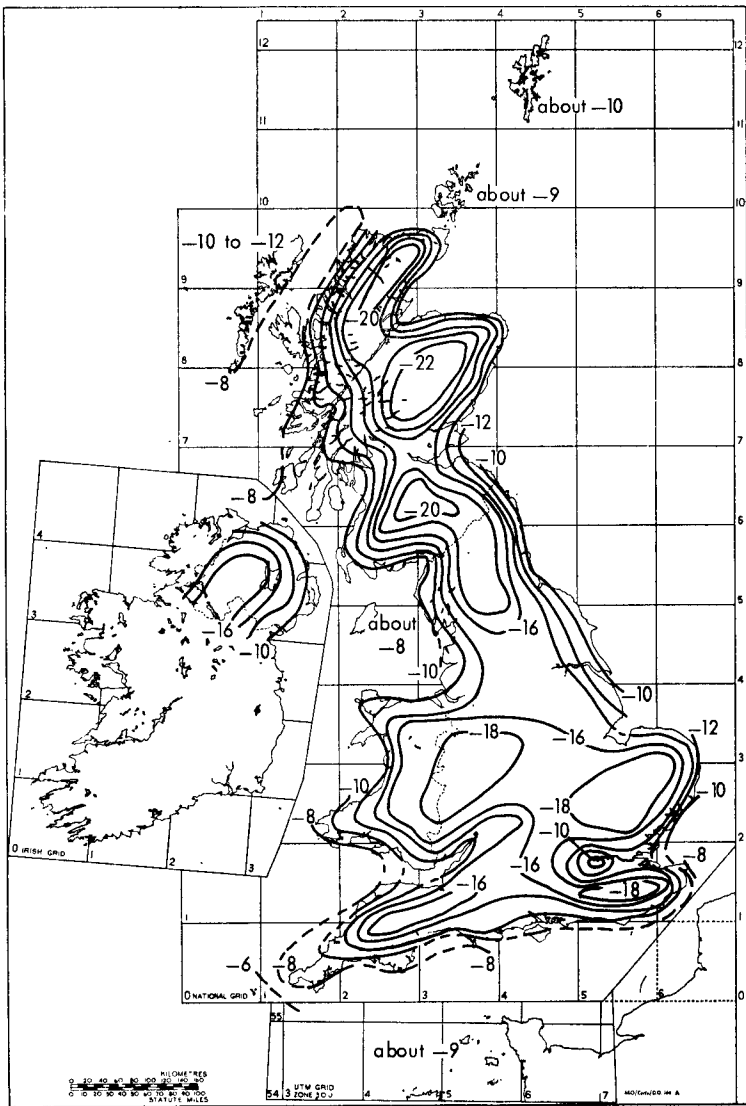


FIGURE 2—ANNUAL MINIMUM TEMPERATURE (IN DEGREES CELSIUS) LIKELY TO OCCUR ONCE IN 50 YEARS AT MEAN SEA LEVEL

To correct for altitude, subtract 0.5 degC per 100 m from map value.

Notes. (a) In sheltered low-lying areas, values are likely to be appreciably lower than map values.

(b) In urban areas (except London), values are likely to be appreciably higher than map values.

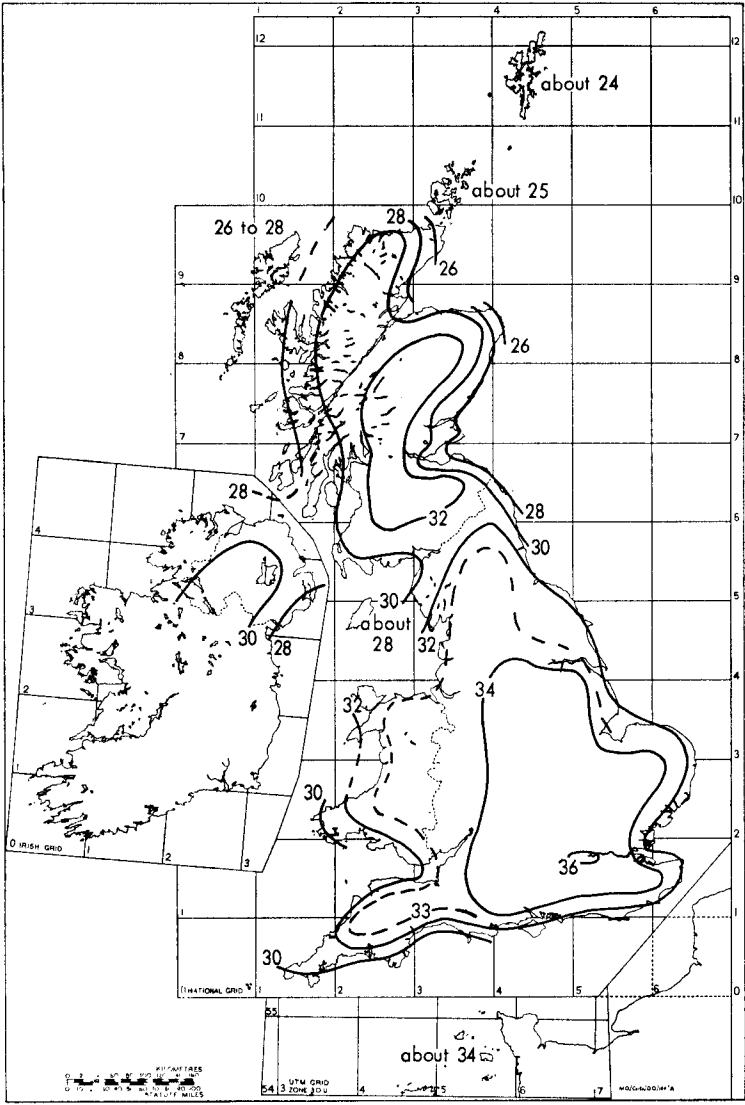


FIGURE 3—ANNUAL MAXIMUM TEMPERATURE (IN DEGREES CELSIUS) LIKELY TO OCCUR ONCE IN 50 YEARS AT MEAN SEA LEVEL

To correct for altitude, subtract 1.0 degC per 100 m from map value.

be expected in open level country (reduced to sea level), and if interpolated values are to be used for design purposes at sites in urban areas or frost hollows, then some further adjustment should be made. The magnitude of this adjustment will obviously depend on local circumstances (detailed topography or urban extent and density), but a couple of examples will serve to show what differences can arise.

The frost hollow at Houghall, about 1.5 km from Durham, has been described by Catchpole⁵ and a change in the position of the Houghall site in 1960 has been documented by Smith.⁶ Because of this site change, for comparison purposes the analysis of the annual minimum temperatures has been carried out for the period 1941–60. From this 20-year record, the estimated once-in-50-year minima at Durham and Houghall (both corrected to mean sea level) are -16.5°C and -24.5°C respectively. Figure 2 has been analysed following the Durham estimate derived from the 1941–70 record, since this value was broadly consistent with the other open country stations in the area, but the above comparison indicates that the 'true' Houghall value may be expected to depart by about -8°C from the local map value. Nottingham Castle, in the centre of the city, has an estimated 50-year minimum of -13.0°C , whereas Sutton Bonington, a rural site less than 15 km to the south-south-west, has an estimated value of -17.5°C (both corrected to mean sea level). The Sutton Bonington value, broadly consistent with other rural sites in the area, has been followed in the analysis of Figure 2, and so the Nottingham estimate departs from the local map value by about $+4^{\circ}\text{C}$.

Estimation of extremes for other return periods. It is desirable to have a simple method of obtaining extreme temperatures for other return periods, given the once-in-50-year maps. For both maximum and minimum temperatures, the slope parameter α , evaluated by the maximum-likelihood fitting of a 2-parameter solution to the weighted series of annual extremes, was plotted on a map. For minimum temperatures, α displayed an overall range of from about -1.0 to -2.5 , and there was a tendency for the lower values to occur inland and for higher values to occur around the coast. This reflects the greater variability of annual minima inland, and shows that for extreme minima the differences between coastal and inland sites are accentuated with increasing return period. Accordingly $\alpha = -1.4$ and $\alpha = -2.2$ were selected as being suitable 'typical' values to apply to coastal and inland sites respectively. For maximum temperatures, the overall range was about 1.0 to 1.5 , and there was a fair degree of spatial coherence, but higher and lower values did not seem to be associated with geography. Accordingly a 'typical' value of $\alpha = 1.4$ was selected as being reasonably representative of the whole country.

These three values of α were then used to construct Figure 4, from which corrections to be applied to the map values can be obtained. It can be seen that a variation in α yields a comparatively small change in the correction (less than 1°C difference at 150-year return period for $\alpha = -1.4$ and $\alpha = -2.2$) and therefore the choice of 'typical' values for α for national coverage seems justifiable for practical purposes.

Acknowledgement. The computer program used to perform the extreme-value analysis was devised by A. F. Jenkinson and written by D. M. Pusey.

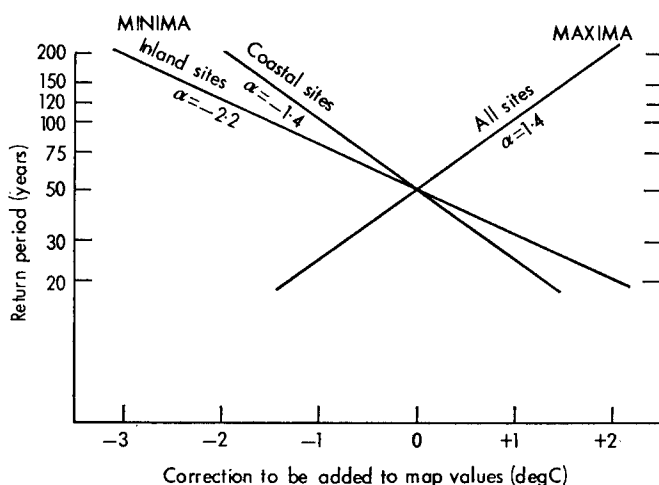


FIGURE 4—CORRECTION DIAGRAM TO BE USED IN CONJUNCTION WITH FIGURES 2 AND 3 TO ESTIMATE EXTREME TEMPERATURES AT OTHER RETURN PERIODS

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COMPUTER QUALITY CONTROL OF DAILY AND MONTHLY RAINFALL DATA

By R. J. SHEARMAN

Summary. An account is given of the quality-control programs recently developed by the hydrometeorological section of the Meteorological Office for routine processing of daily and monthly rainfall data.

Introduction. Daily rainfall totals are measured at approximately 6000 locations throughout the United Kingdom and monthly rainfall totals are recorded at a further 1500 sites. All the daily and monthly rainfall totals are communicated to the hydrometeorological section of the Meteorological Office at Bracknell during the month following that in which the readings were

taken. The large quantity of rainfall data, approximately 180 000 values each month, inevitably contains a substantial number of errors. There are many possible reasons for incorrect data, including rainfall-observing errors, etc. Before the data can be used for any serious hydrological or hydro-meteorological investigation, these errors must be identified and corrected by some form of quality control.

Manual checking of rainfall data is not practicable when the number of rainfall stations exceeds one thousand. A computerized objective method is required to control the quality of rainfall data for the United Kingdom rain-gauge network. Such a method involving English Electric KDF9 computer programs was used by the Meteorological Office during the years 1964–72, but even this method (Allen¹) was too slow to meet many operational requirements. During 1973 a new set of quality-control programs was brought into operational use. These programs utilize the speed and large storage capacity of the IBM 360/195 computer recently installed at the Meteorological Office Headquarters, Bracknell. The new quality-control routines for daily rainfall totals (Figure 1) can be considered as being composed of four separate stages. The quality control of monthly rainfalls will be discussed later.

The calculation of an interpolated rainfall value. An objectively estimated rainfall value at the station under scrutiny is obtained by interpolating between the rainfall values at surrounding stations. The initial selection of neighbouring stations would be an arduous task if it were performed manually, therefore an objective method has been programmed which is flexible enough to take account of recently established rainfall stations.

Ideally the stations selected as neighbours should be physically representative of the area in which the station under scrutiny is situated. With this aim in view only stations within a circle of radius 25 km are considered, and a maximum of two stations allowed in each octant of this circle. The latter condition ensures that the neighbours are reasonably evenly distributed. Eight neighbours are chosen and their identifiers are stored with the daily data for each station in the rainfall archive.

Before interpolation, suspect neighbouring values are filtered out, leaving a maximum of six mutually consistent totals for each day, and each of these is converted to a percentage of the appropriate station's annual average rainfall. The use of percentages enables the interpolation procedure to take into consideration the variations in rainfall due to topography.

A weighted mean is used to compute an interpolated rainfall, with weights inversely proportional to the square of the distance:

$$R = \frac{\sum_i \frac{R_i}{D_i^n}}{\sum_i \frac{1}{D_i^n}},$$

where R = interpolated rainfall (percentage of annual average),
 R_i = rainfall at station i (percentage of annual average),
 D_i = distance between neighbour i and station under scrutiny in kilometres, and
 $n = 2$.

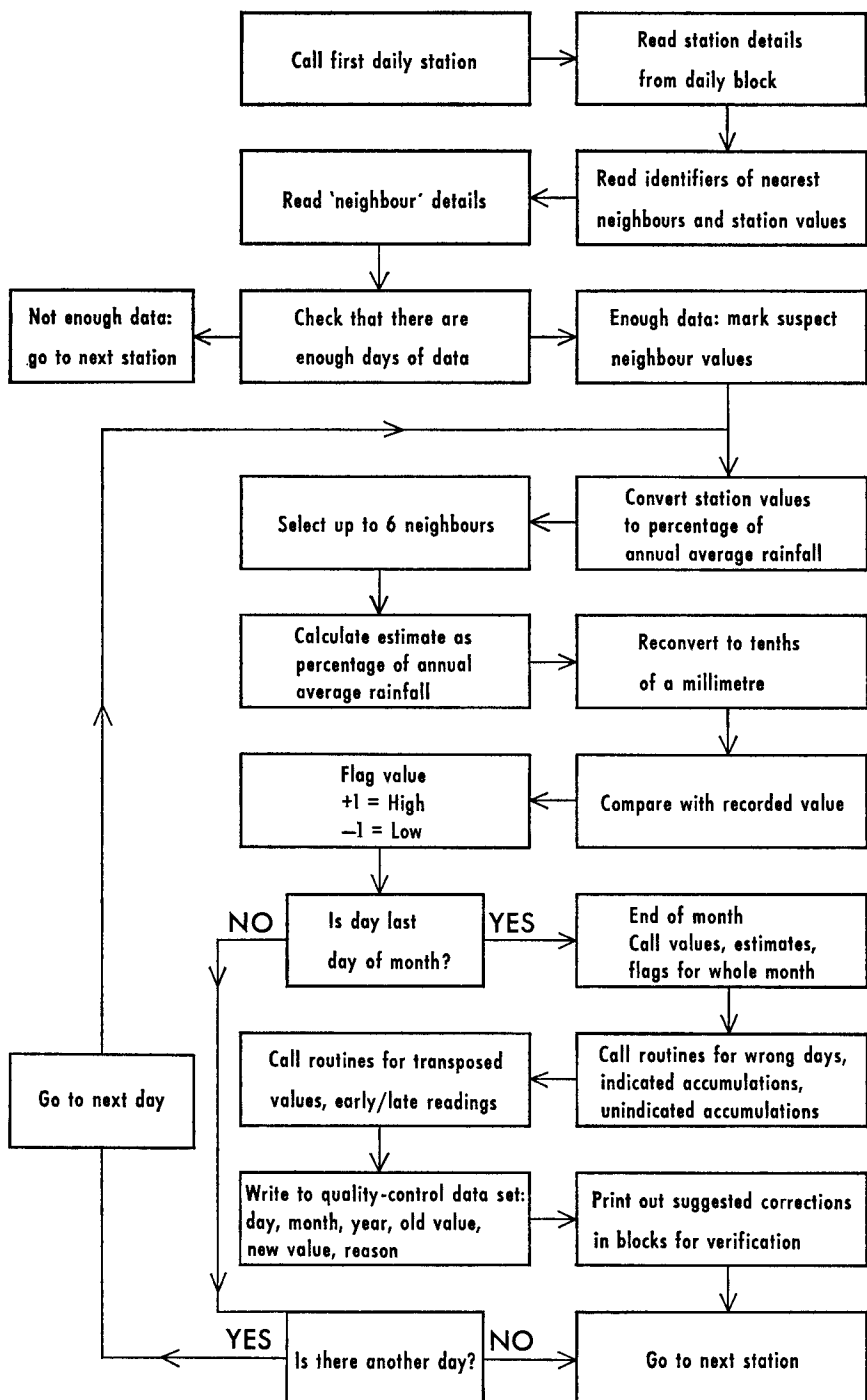


FIGURE 1—STEPS IN DAILY QUALITY-CONTROL PROGRAM

By 'details' in for example block 2 is meant such information as National Grid Reference, station annual average rainfall, etc.

If $n = 1$, it has been found that maxima and minima are accentuated, and undue weighting is given to distant stations. Kelway² has shown that $n = 1.65$ is an optimum value for a particular station network. For the United Kingdom rain-gauge network $n = 2$ gives equally good results. Some experiments have been carried out to obtain interpolated values by fitting a plane to the data by using a least-squares technique, but the operational advantage of adopting this method are not obvious.

Comparison of recorded rainfall with estimated value. The difference between the recorded and the estimated value is considered to be insignificant if the following conditions are met:

$$\begin{aligned} |\text{DIFF}| &\leq 2.5 \text{ mm, and} \\ |\text{DIFF}| &\leq C \times \text{error in estimate.} \end{aligned}$$

DIFF = difference between recorded and estimated values and C = constant (2.0 for daily quality control and 4.0 for monthly quality control). These values were determined empirically, using the experience of scrutineers to assess the action of the program. If the difference is unacceptably high, the figure is flagged +1 or -1, depending on whether the observed total is greater or less than the estimate.

Identification of commonly occurring errors. There are five commonly occurring errors which are suitable for automatic amendment. These are:

- (a) Wrong days;
- (b) Indicated accumulations;
- (c) Unindicated accumulations;
- (d) Transposed values; and
- (e) Incorrect time of observations.

(a) *Wrong days.* Often an observer will credit the rainfall to the wrong day, for all or part of a month, or alternatively he may put too many or too few zeros in a dry spell, resulting in the rest of the month's values being one or two days out of phase. The amendment routine allocates the observed rainfall totals to the correct day. This is done by shifting the rainfall values backwards and forwards one or two days and correlating the observed data with the interpolated values. The day-shift giving the highest correlation coefficient greater than 0.95 is taken as authentic. Any embedded accumulations are apportioned with this shift applied.

(b) *Indicated accumulations.* It is inevitable that rainfall will occasionally accumulate because an observation has been missed; this is particularly so now that many organizations are working a five-day week. The observer normally marks any accumulations clearly before sending the record to the Meteorological Office. It is relatively simple to apportion the accumulated total in the ratio of the estimated values on the day concerned by using the relationship

$$R_i = \frac{R_{tot}}{\sum_i RE_i} \times RE_i$$

where R_i = apportioned rainfall for day i ,
 R_{tot} = accumulated total, and
 RE_i = estimated rainfall on day i .

(c) *Unindicated accumulations.* Sometimes an accumulation is not marked, and must be identified before any attempt can be made to apportion the total. This is done by seeking a +1 flag and searching backwards and forwards for a period of 10 days and accepting days with -1 flags and no rainfall, but terminating the run when a day with measurable rainfall is found. The accumulated total is then apportioned by use of exactly the same method which is applied to indicated accumulations.

(d) *Transposed values.* Values may be transposed owing to clerical or other error; the routine is designed to look for pairs of \pm flags, and to compare the recorded rainfall on the day flagged +1 with the estimate on the day flagged -1, and vice versa. The values may be transposed if the following relationships hold:

$$\begin{aligned} | \text{DIFF} | &\leq 2.5 \text{ mm, and} \\ | \text{DIFF} | &\leq C \times \text{error in estimate,} \end{aligned}$$

where DIFF = difference between recorded rainfall total and estimated value, and C is the constant defined above.

(e) *Incorrect time of observation.* In many cases it is impossible for an observer to measure the rainfall total at the nominal time; a delay of an hour or two may occur, and in extreme cases a delay of several hours. If there is appreciable rainfall during this time the rainfall total for one day will be enlarged and that for the next day decreased.

The computer program identifies continuous runs of +1 and -1 flags and calculates the sum of the recorded values and the sum of the estimates for each run. If the two totals agree within the limit imposed by the two criteria

$$\begin{aligned} | \text{DIFF} | &\leq 2.5 \text{ mm, and} \\ | \text{DIFF} | &\leq C \times \text{the combined error in the estimate,} \end{aligned}$$

where DIFF is the difference between the totals, then an apportionment is made between the days of the run by using the ratio

$$R_i = RE_i \times RTOT / \sum_i RE_i,$$

where R_i = apportioned value on day i ,
 RE_i = estimated value on day i , and
 $RTOT$ = sum of recorded values in run.

Apportioned values are flagged to indicate the reason for the change.

Storage of amended data on archival rainfall-data disc. The final step in any operational quality-control scheme is the automatic correction of erroneous data, and an indication of the reasons for the amendment. Such a step is being developed, and will eventually be included in the quality-control routines.

The amended values suggested by the computer program are written into the rainfall archive, but data must never be lost by computer action, and therefore a corresponding entry is made in the quality-control data set. This entry consists of station number, date, the original rainfall total, the corrected value, and a reason for the change. Thus the data can be reconstructed if the computer action is judged unnecessary by the scrutineers.

Quality-control of monthly rainfall totals. Figure 2 shows an outline of the steps in the program used to check monthly rainfall totals. Nearest-neighbour stations are used to produce an estimated rainfall total in exactly the same way as for quality control of daily totals. The program then compares both the recorded monthly total and the sum of the daily 'best-estimate'

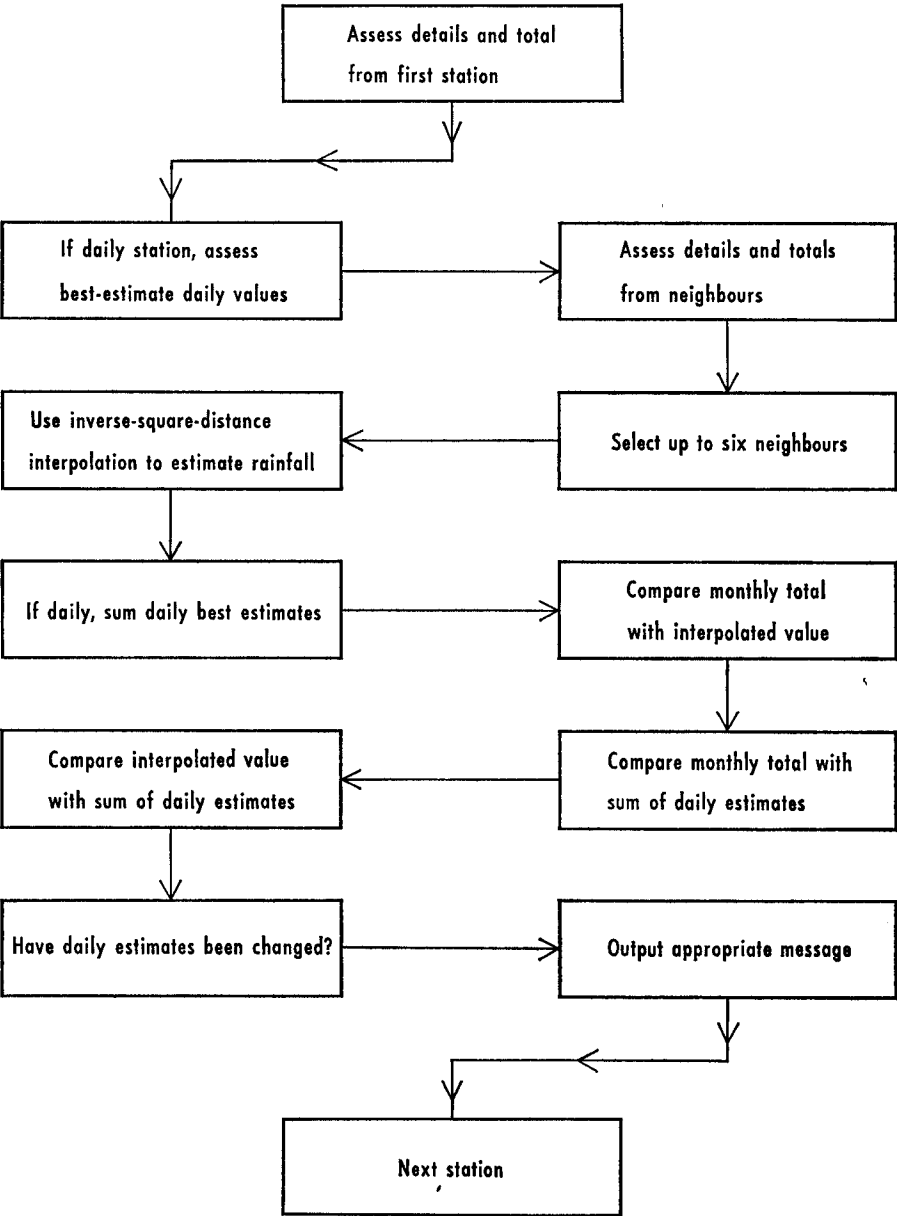


FIGURE 2—STEPS IN MONTHLY QUALITY-CONTROL COMPUTER PROGRAM

totals with the estimated monthly total. The latter comparison acts as a check on the daily quality control. Inconsistencies are flagged, and an error message printed out as guidance for the scrutineer. No attempt is made to amend totals automatically, any alterations being entered manually after verification.

Conclusion. The quality-control routines described in this paper have proved to be a useful tool for operational processing of rainfall data. Computing a rainfall value for comparison purposes by interpolation from surrounding observations is an improvement on previous methods, which were based on area means. The large storage and high speed of the IBM 360/195 computer have enabled the scheme outlined in this paper to control in one operation the quality of a whole month of data from every station in the national network. The time taken for this task is about 30 minutes. Subsequent scrutiny takes a minimum of three weeks at present and is necessary not only to check computer action, but also to resolve cases which the computer is unable to deal with.

There is scope for further experiment with interpolation techniques: a least-squares method of fitting a plane to the data could possibly give a better interpolated value. However, it is doubtful whether a more advanced method than this would be worth while. The constant factor used in flagging errors could be varied regionally in order to reflect the density of the rain-gauge network. It is also desirable, in any automatic rainfall quality-control system, to relate the thresholds used for flagging data to the synoptic situation. The thresholds used operationally are a compromise, giving a reasonably good quality control in most circumstances, but obviously the tolerance allowed before a value is declared erroneous in frontal rain should be different from that used in a very unstable showery situation.

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551-577-37

THE HEAVY RAINFALL OVER NORTHERN ENGLAND IN JULY 1973*

By M. J. PRIOR

Summary. During 15 and 16 July 1973, heavy rainfall occurred over a large area of northern England and the North Midlands. Some places had their heaviest 24-hour and 48-hour rainfalls since records began, and the long duration and large area affected by the fall resulted in widespread flooding, especially in areas adjacent to the southern Pennines.

Introduction. This paper is based on a detailed examination of the heavy rainfall which occurred over a large area of northern England and the North

* This paper is a shortened version of an unpublished report entitled 'The heavy rainfall of mid July 1973' available in the Meteorological Office, Bracknell.

Midlands on 15 and 16 July 1973 and of the meteorological situation which caused it, and as such it complements an earlier article by P. A. Smithson.¹

The rainfall

Spatial distribution. In the 24-h period beginning at 09 GMT on 15 July 1973 totals in excess of 25 mm were measured over a large part of northern England and the North Midlands, and it has been estimated that over 10 000 km² of northern England had more than 50 mm of rainfall; the areas which received amounts in excess of other thresholds are given in Table I.

TABLE I—THE SIZES OF AREAS WITH RAINFALL GREATER THAN SPECIFIED AMOUNTS IN MID JULY 1973

Period	Size of area with rainfall exceeding			
	150 mm	125 mm	100 mm	75 mm
	square kilometres			
15/09 GMT–16/09 GMT	—	110	620	2600
15/09 GMT–17/09 GMT	240	700	2240	7300

A notable feature of the rainfall distribution was the effect of topography, with the higher totals over and to the east (the windward side) of the Pennines and further heavy falls over the Lincolnshire Wolds, as shown by the isohyetal map for the 48-h period beginning at 09 GMT on the 15th (Figure 1). The 2-day totals, however, resulted not only from frontal rainfall but also from thunderstorms which occurred late on the 16th; these storms gave rainfall amounts exceeding 25 mm in places south-east of the Pennines. The highest 2-day totals were recorded at Derwent Dam (169.7 mm), Howden Dam (167.6 mm) and Rivelin (165.4 mm), all in the southern Pennines. The highest 24-h totals were also measured at these places and details of these and other 24-h totals are given in Table II.

The 119.2 mm recorded at Sheffield on the 15th was the heaviest fall there in a rainfall day since records began in 1881 and the significance of this and of the other 24-h and 48-h rainfalls which were measured east of the Pennines is emphasized when these falls are considered as percentages of the 1916–50 average annual rainfall (AAR). The return period of the rainfalls of various durations is discussed later.

Temporal distribution. Two sources of rainfall affected northern England and the North Midlands during the period 15–17 July. These were:

- (a) a prolonged period of heavy rainfall which moved in from the east early on the 15th and intensified early on the 16th, after a lull during the evening of the 15th, and
- (b) thundery rain which moved in from the south late on the 16th.

An analysis of tilting-siphon autographic rain-gauge records for about 25 rainfall stations located across northern England made it possible for a study to be made of rainfall as a function of time. Graphs of the cumulative rainfall amounts versus time at four representative sites are given in Figure 2. The graphs show the two periods of heavy rainfall referred to above and cover a period of about 26 hours. The westward movement of the heavier rain and the slow clearance from the south-east on the 16th are also well illustrated.

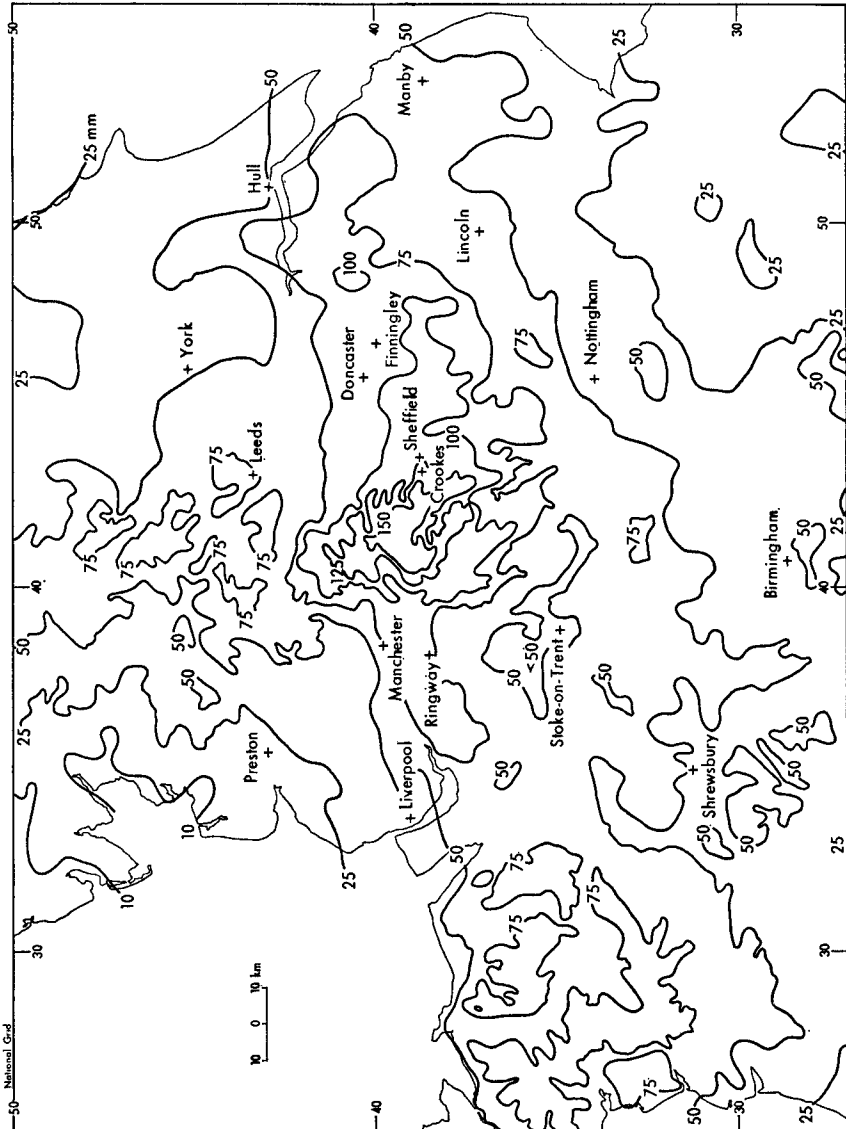


FIGURE 1—RAINFALL IN MILLIMETRES FOR THE 48 HOURS BEGINNING AT 09 GMT ON 15 JULY 1973
FOR NORTHERN ENGLAND AND NORTH WALES

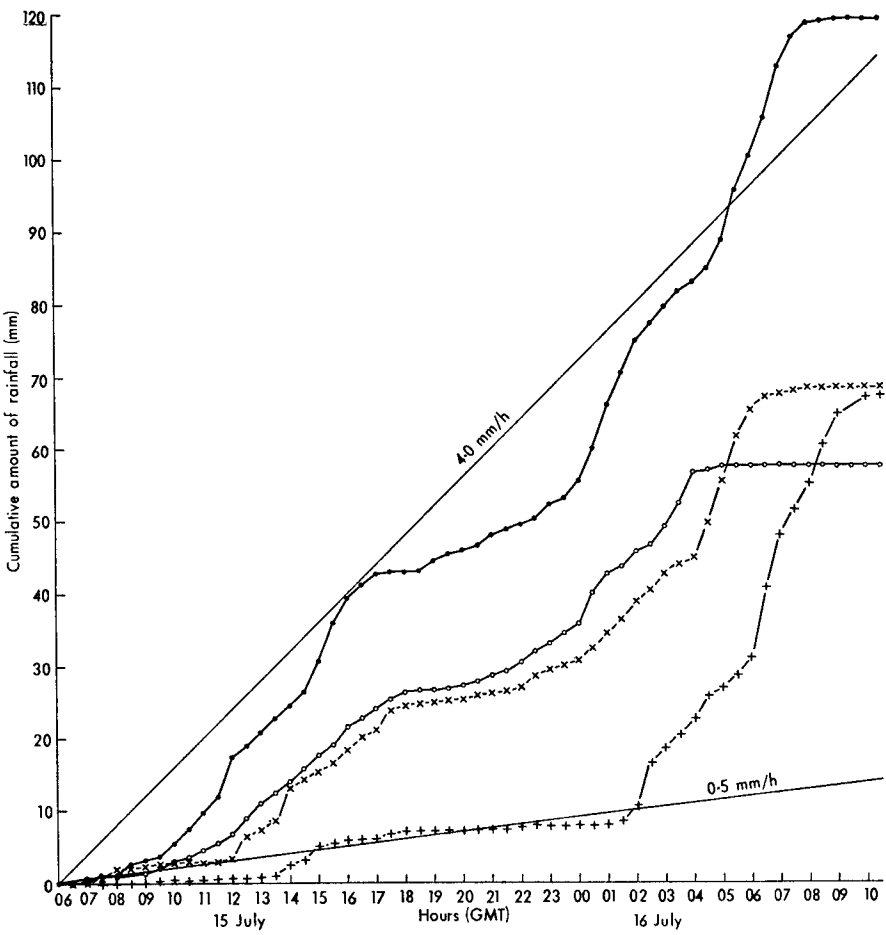


FIGURE 2—GRAPHS SHOWING CUMULATIVE AMOUNTS OF RAINFALL FOR FOUR RAINFALL STATIONS IN NORTHERN ENGLAND FOR THE PERIOD 06 GMT, 15 JULY TO 1030 GMT, 16 JULY 1973

Graph	Station	Number	Grid Reference	Altitude (m)
+ — +	Ringway, Manchester*	564419	(33)818850	76
● — ●	Crookes, Sheffield	082580	(43)330872	192
x — x	Finningley, Notts.	125843	(43)658988	10
○ — ○	Manby, Lincs.*	136580	(53)391869	17

These graphs have been compiled by using tilting-siphon autographic records, the totals of which have been adjusted to secure agreement with the stations' check gauges.

* It was necessary to use a tipping-bucket record to complete the graphs for Ringway after 09 GMT on 16 July and for Manby before 09 GMT on 15 July.

In the context of frontal rainfall, that falling at a rate between 0.5 mm/h and 4.0 mm/h is classed as moderate, rain falling at a rate >4.0 mm/h is termed heavy, and a rate <0.5 mm/h is classed as light.

The location of the four stations is given in Figure 1.

Further heavy, thundery rain (not shown in Figure 2) moved into most of northern England by 21 GMT on the 16th and lasted until 06 GMT on the 17th in some parts.

Return periods and comparisons. The hydrometeorological section of the Meteorological Office has estimated the annual and seasonal return periods of the rainfall amounts measured in mid July 1973, by using the methods which were developed in the Flood Studies Project.² The annual return periods of some of the 24-h totals are of the order of hundreds of years (Table II), but over shorter durations the rainfall event was not so remarkable. The return periods of the 24-h totals were also calculated for the summer half-year (May–October) and the winter half-year (November–April) and it was found that the amounts recorded in the Sheffield area for example are two to three times more likely to fall there in summer than in winter. Similar results were obtained for other districts to the east of the Pennines and these are in agreement with Bleasdale's conclusion³ that exceptionally heavy falls are predominantly a summer half-year phenomenon in the areas with lower average annual rainfall (i.e. eastern areas).

The return periods of the areal rainfall over the areas with 2-day rainfall greater than 100 mm and 150 mm were estimated to be 200 years and 500 years respectively. However, the return period of a similar rainfall event occurring in some part or other of Lincolnshire, Nottinghamshire, Derbyshire or Yorkshire is perhaps of the order of 25 years, as suggested by Table III.

On a depth-area-duration basis, events similar to that of July 1973 appear to have been those of 13–15 October 1892⁴ and 6–7 August 1922.⁵ Moreover, the meteorological situations which caused these two falls of rain in some respects resemble the situation which prevailed in mid July 1973. On both occasions a slow-moving deepening low-pressure area lay over or near the English Channel, and eastern England experienced prolonged rainfall accompanied by strong east-north-east winds. The meteorological situation and its development on 14–15 September 1968⁶ also had much in common with the 1973 event, although a different and larger area was affected in 1968 (Table III).

The meteorological situation. The meteorological situation at 00 GMT on the 15th is depicted in Figure 3. The main features are (a) the slow-moving low-pressure area centred to the south-west of the United Kingdom, (b) the contrasting air masses and (c) an easterly flow over Scotland. The front over western France marked the boundary of cold polar maritime air, which was being advected round the depression and towards England. The cold occlusion, which had resulted from an earlier burst of cold air, was preceded by a very moist, warm air mass of western Mediterranean origin and a strong low-level easterly flow was continuously conveying this abundant supply of moisture-laden air towards England.

The first period of heavy rainfall over northern England on the 15th was associated with the cold occlusion (Figure 4). After a lull in the rainfall during the evening of the 15th the arrival of a fresh supply of cold air, associated with the cold front, led to the development of further heavy rainfall which lasted for most of the morning of the 16th (Figure 2). The rainfall area moved very slowly northwards and westwards and tended to die out as it did so as a result of the continual occluding process of the frontal system.

TABLE II—TWENTY-FOUR-HOUR RAINFALL AMOUNTS EQUALLING OR EXCEEDING 100.0 mm RECORDED IN NORTHERN ENGLAND
ON 15 AND 16 JULY 1973

Station number	Name	National Grid reference	Amount mm	Estimated return period years	Percentage of Average Annual Rainfall for 1916-50	Period (GMT)
078701	Ramsden	(44)116051	104.9	90	6.8	15/0900-16/0900
081548	Harden	(44)150035	109.3	80	7.8	15/0900-16/0900
081875	Flouch Road	(44)205004	101.9	110	9.1	15/0800-16/0800
081892	Langsett Res.	(44)211003	108.2	150	10.2	15/0800-16/0800
081895	Upper Midhope	(43)215999	102.8	100	9.6	15/0800-16/0800
081915	Midhope	(43)219994	103.4	110	8.8	15/0700-16/0700
082093	Broomhead Res. No. 2	(43)272959	106.3	210	12.0	15/0800-16/0800
082111	Morehall Res.	(43)289957	108.3	250	12.7	15/0800-16/0800
082295	Bradfield Filters	(43)261016	121.5	320	12.1	15/0800-16/0800
082512	Redmires Res.	(43)267856	116.0	320	10.9	15/0800-16/0800
082527	Rivelin	(43)287869	137.4	840	14.5	15/0800-16/0800
082580	Crookes	(43)330872	117.4	450	14.5	15/0800-16/0800
082583	Sheffield	(43)339873	119.2	540	15.3	15/0900-16/0900
082851	Sheffield, Riverdale Road	(43)324859	116.9	430	14.6	15/0900-16/0900
084834	Aldwarke S. Wks	(43)444943	105.4	390	16.6	15/0900-16/0900
084927	Firsby Res.	(43)495958	114.3	520	16.9	15/0900-16/0900
085831	Wortley Res.	(43)308098	100.3	210	12.3	15/0700-16/0700
106238	Howden Dam	(43)168924	128.7	200	10.0	15/0800-16/0800
106295	Derwent Dam	(43)175899	133.8	320	10.1	15/0800-16/0800
106430	Wood Cottage	(43)128896	108.5	100	7.1	15/0900-16/0900
106601	Bamford Filters	(43)212830	107.4	190	10.5	15/0900-16/0900
106869	Bamford	(43)202829	112.0	240	11.1	15/0800-16/0800
107149	Eyam Hall	(43)217764	106.8	200	11.4	15/0900-16/0900
107268	Barbrook Res.	(43)281770	108.5	250	11.9	15/0800-16/0800
124801	Ranskill S. Wks	(43)668878	139.0*	1430	23.7	15/1400-16/1400
558489	Kinder Filters	(43)054880	124.7	180	10.7	15/1030-16/1030

* The total measured at Ranskill S. Works (North Nottinghamshire) is suspect when compared with the neighbouring values of about 80 mm for the wetter 24-h period beginning 15/0900 GMT.

TABLE III—DATES, PLACES AND ESTIMATED AREAS AFFECTED BY FIVE WIDESPREAD, HEAVY FALLS OF RAIN IN EASTERN ENGLAND

Dates and areas affected	Size of area with rainfall exceeding				
	200 mm	150 mm	125 mm	100 mm	75 mm
13-15 Oct. 1892 Yorks., Lincs.	—	50	600	2900	8000
6-7 Aug. 1922 Yorks., Derby., Notts.	—	—	350	2300	8600
3-4 Sept. 1931 Yorks., Derby., Notts.	Not yet calculated, but very large				
14-15 Sept. 1968 South-east England	13	575	2350	6250	12500
15-16 July 1973 Yorks., Derby., Lincs.	—	240	700	2240	7300

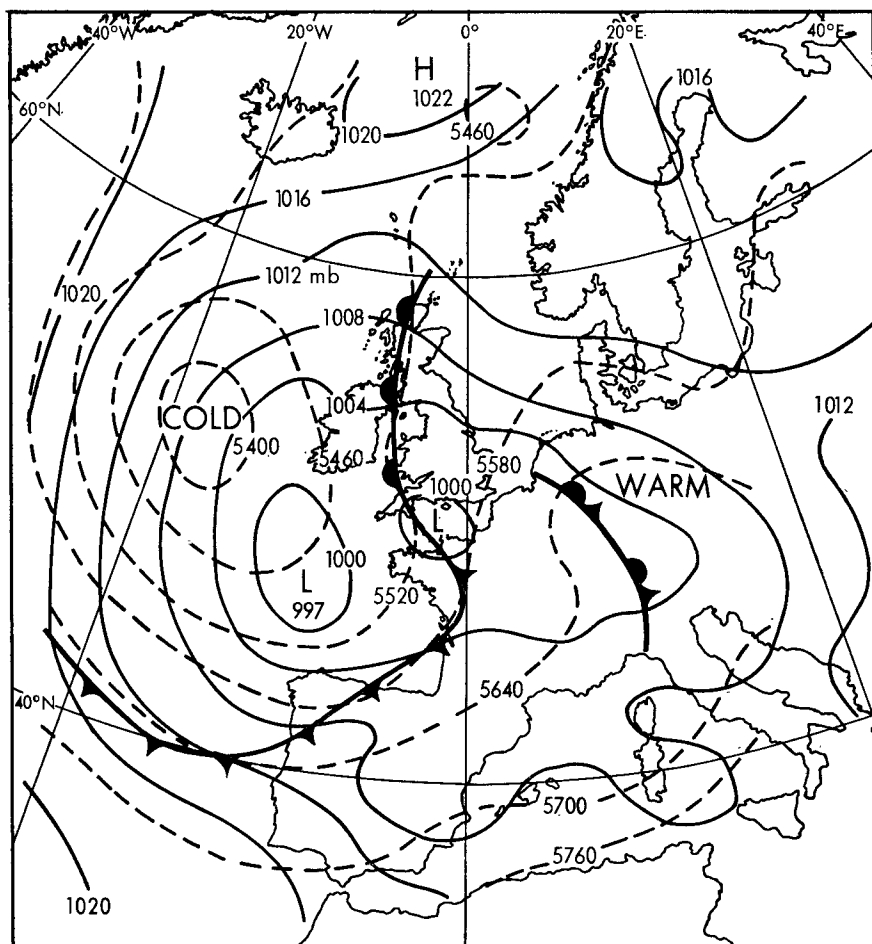


FIGURE 3—SURFACE AND 1000-500-mb THICKNESS CHART FOR 00 GMT ON 15 JULY 1973

———— Surface pressure - - - - 1000-500-mb thickness in geopotential metres

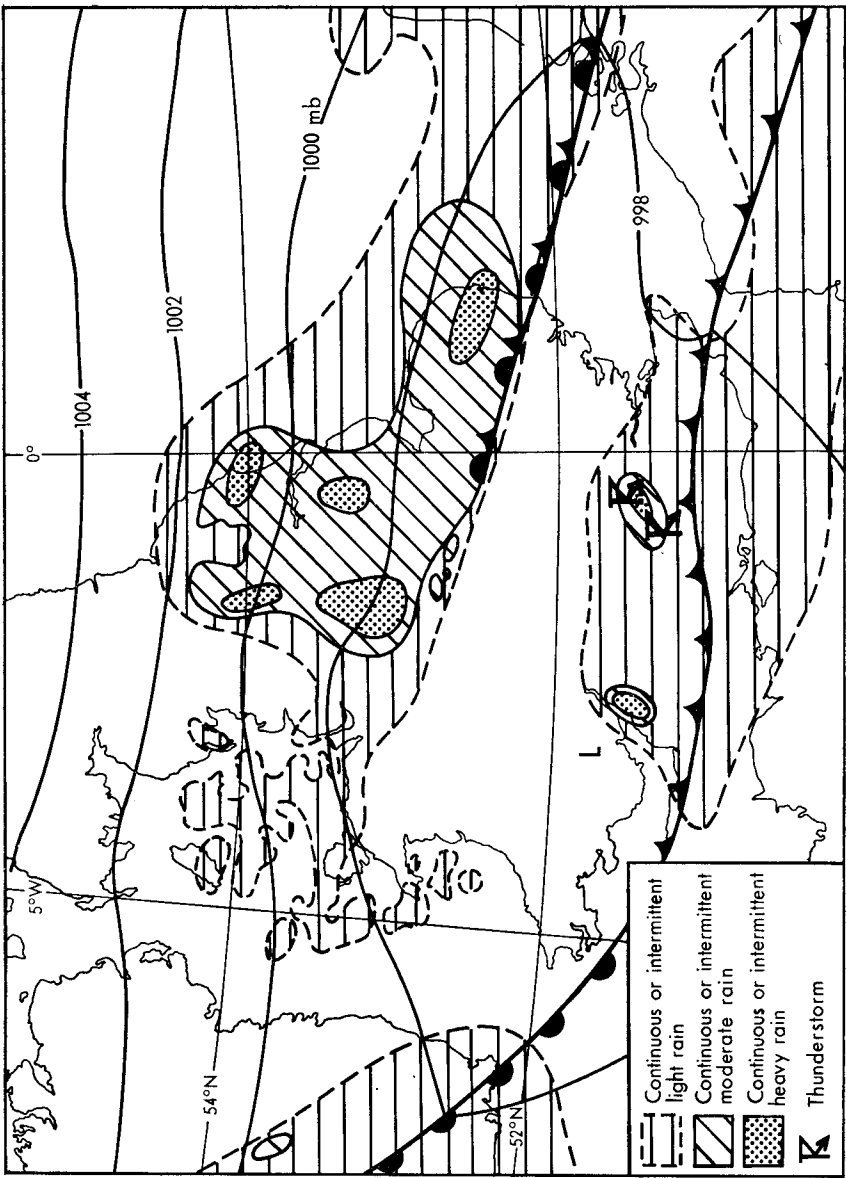


FIGURE 4—SURFACE CHART FOR 12 GMT ON 15 JULY 1973

The processes which produced the rainfall over northern England were (a) low-level convergence chiefly as a result of surface friction, (b) forced ascent of the moist easterly airstream by topography and (c) ascent of the easterly flow at the frontal surface. High pressure was maintained to the north of the British Isles and this had an overall blocking effect which helped to maintain the rather strong easterly flow and hence the supply of warm moist air.

The subsequent pool of very cold air, extending to high levels, was associated with the depression over southern England at 00 GMT on the 16th (Figure 5).

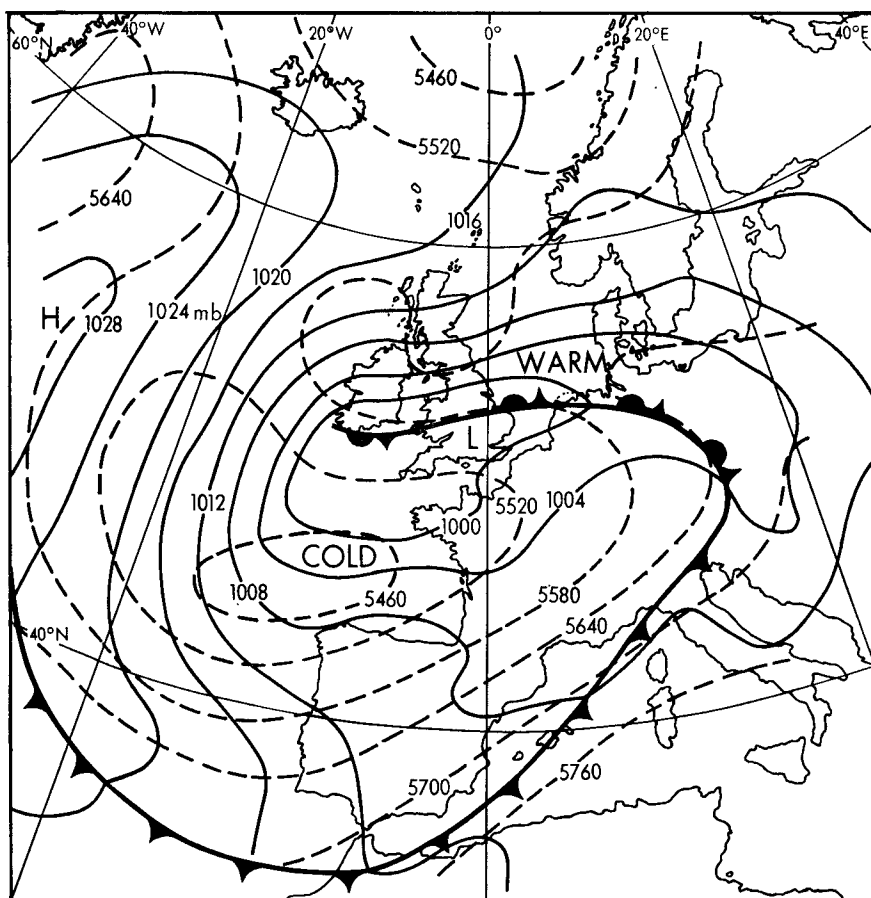


FIGURE 5—SURFACE AND 1000-500-mb THICKNESS CHART FOR 00 GMT ON 16 JULY 1973

—— Surface pressure --- 1000-500-mb thickness in geopotential metres

Such conditions are ideal for the development of thunderstorms, especially over land during the summer months. Thunderstorms had developed over southern parts of the country by 12 GMT on the 16th (Figure 6) and the

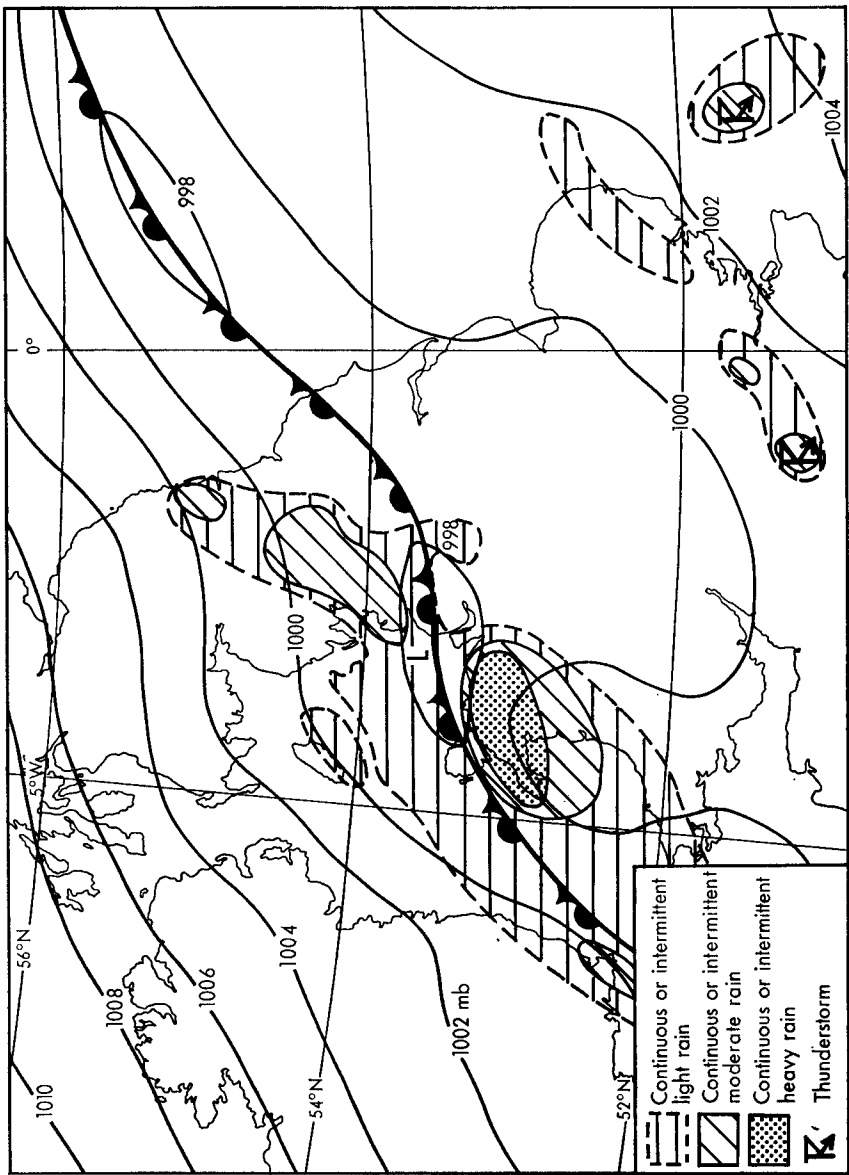


FIGURE 6—SURFACE CHART FOR 12 GMT ON 16 JULY 1973

thunderly rain became more organized whilst it moved northwards. The rainfall attributed to these thunderstorms amounted to more than 25 mm in some parts of northern England.

The July 1973 rainfall event occurred when (1) the soil moisture deficit (SMD) was large in parts of northern England (over 100 mm SMD in west Yorkshire on 11 July) and (2) the south Pennine reservoirs were about 75 per cent full. Hence both the soil and the reservoirs were capable of absorbing a significant proportion of the rainfall and the subsequent flooding (principally in the valleys of the Rivers Mersey, Don, Rother, and Derbyshire Derwent) was not as disastrous as it might have been.

It is of interest to consider whether a similar rainfall event could happen in the winter months when conditions (1) and (2) above might not apply. The possibility of a negative answer to this question has been indicated in the section dealing with return periods and comparisons, and this is cautiously confirmed by meteorological considerations. The criteria for this type of prolonged rainfall are the proximity of a slow-moving depression—preferably to the south or south-west—with a flow of moist air being forced to ascend in a quasi-stationary convergent zone. The higher the temperature of this air, the greater its capacity to hold moisture and thus, in general, summer and early autumn are the favoured seasons for very heavy rainfall in eastern England.

Acknowledgement. I should like to thank my colleagues in the hydro-meteorological section of the Meteorological Office for their assistance in the preparation of this paper, and in particular Mr M. C. Jackson and Mr P. Wescott for their contributions to the section dealing with return periods and comparisons.

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REVIEWS

An introduction to agrotopoclimatology, WMO Technical Note No. 133, by L. B. MacHattie and F. Schnelle. 275 mm × 210 mm, pp. xii + 131, *illus.*, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1974.

Although much of the subject matter of this *Technical Note* has been studied for centuries (under local climatology, and, more recently, mesoclimatology) the upsurge of interest which followed the Second World War in urban climate, in the control of industrial pollution, in certain aspects of aviation and aerospace activities and particularly in agricultural meteorology, has inevitably

resulted in the need to amass, codify, synthesize and extend our knowledge of the effects on the climate of the lowest few tens of metres of the atmosphere exerted by the physiographic and physical properties of the earth's surface. K. Knoch (in Germany) and C. W. Thornthwaite (in the U.S.A.) firmly established these studies in the early 1950s and adopted the term 'topoclimatology' to distinguish it from the associated microclimatology. The further restriction to *agrotopoclimatology* is self-explanatory.

The publication consists of (1) Introduction (pp. 1-4); (2) Elements of topoclimatology (pp. 5-17); (3) Conduct of agrotopoclimatological surveys (pp. 18-31); (4) Examples of surveys (pp. 32-35); (5) Bibliography (pp. 36-110)—an extended list (hardly the 'survey' as described in the Summary) of over 1000 items (arranged alphabetically by authors) and followed by titles and publishers of some 160 relevant scientific journals in which, nevertheless, the valuable series of Proceedings of Symposia held partly under UNESCO auspices is merely referred to as 'UNESCO Publications'.

Chapters 1 and 4 might well be read first to indicate the problems, motivation and investigational procedures. The remainder will be found to pack a considerable amount of information into the few pages devoted to each individual topic.

There is proper emphasis in Chapter 3 on the fact that the design of any investigation, the required observational accuracy and procedures etc., are significantly governed by the practical objectives which are typical of studies in agricultural meteorology. It is stressed, for example, that one needs to consider how data are to be analysed and presented before deciding upon the type and scheduling of the observations. Portions of this chapter may appear inappropriate for a *Technical Note*, but it must be realized that, in developing countries, WMO publications may well be the only authoritative, comprehensive and up-to-date meteorological literature available to the Meteorological Service.

Any reviewer can note some omissions, e.g. the parametric description of landscape, the effect on surface airflow of arrays of definable obstructions, and ground surface temperatures—but, all in all, this is a useful and by no means premature compilation.

R. W. GLOYNE

Solar activity and related interplanetary and terrestrial phenomena (Volume 1 of Proceedings of the First European Astronomical Meeting, Athens, 4-9 September 1972, edited by J. Xanthakis. 250 mm × 170 mm, pp. xv + 195, illus., Springer Verlag, 1 Berlin 33, Heidelberger Platz 3, Berlin-West, 1973. Price: DM 94.

In an attempt to bring European astronomers into close contact with each other, the Greek National Committee for Astronomy organized the first European Regional Meeting in Athens in September 1972. This book is one of three volumes covering the proceedings and is restricted in subject matter to the solar system. The second and third volumes are concerned with 'Stars and the Milky Way System' (edited by L. N. Mavridis) and 'Galaxies and Relativistic Astrophysics' (edited by B. Barbanis and J. D. Hadjidemetriou) and neither of them contains papers of interest to meteorologists.

Following a review paper on Interplanetary Solar Phenomena by L. D. de Faiter, the discussion of solar activity deals mainly with solar-cycle studies and indices of activity and leads to discussions of correlations with terrestrial and lunar effects.

Meteorologists may be interested in the paper on Solar Activity and Precipitation by J. Xanthakis. In recent years there has been considerable discussion on the possible effects of variable solar activity on various meteorological and climatological phenomena. This paper joins the growing list of statistical analyses of the problem, but like many other contributions in this field, the paper is devoid of hypotheses to explain what is happening. Annual precipitation data for the northern hemisphere were examined for long-term periodicities and the results are suggestive of the influence of solar activity.

The empirical-statistical links between variable solar activity and large-scale meteorological phenomena are tantalizing. But we should guard against drawing strong conclusions until these results have been quantitatively analysed within a general meteorological framework.

There are four papers on planetary atmospheres in this volume; they are all very poor, and written in a parochial manner suggesting that all authors have little or no knowledge of the wealth of literature already published in their chosen fields. The discussions of the Martian atmosphere are the worst. Although they were written in 1972, no results are included from the MARINER 9 mission which radically changed our view and understanding of the Martian atmosphere.

The remaining articles in the volume are concerned with X-ray astronomy and discussions of large national and international astronomical projects and plans for the future development of ground-based and satellite installations for studying solar activity.

This book is very expensive and covers a rather limited scientific field both in content and in depth. I cannot believe that many libraries will buy it and certainly very few people will feel that this book is a worthwhile purchase. The small scientific community interested in this subject would have been better served with a less expensive 'conference proceedings' available more quickly after the meeting.

G. E. HUNT

Arizona climate 1931-1972, revised second edition, edited by William D. Sellers and Richard H. Hill. 240 mm × 310 mm, pp. vii + 616, *illus.*, The University of Arizona Press, Box 3398, Tucson, Arizona 85722, 1974. Price: \$18.00.

This is the second edition of a book first published in 1964. About 40 pages are devoted to a general description of the climate of Arizona, and this is related to synoptic meteorology through consideration of the characteristic weather patterns leading to extreme temperatures, maximum precipitation and snowfall within Arizona. This section also presents the available data on

wind direction and speed, cloudiness and evaporation. The major part of the volume, over 540 pages, consists of temperature and precipitation data for over 330 stations. There is a brief text describing the topography, vegetation and climate of each station, accompanied by a summary giving monthly and annual means and extremes. There are a number of photographs illustrating the varied topography of Arizona, but these are without captions and do not appear to relate specifically to the surroundings of the climatological stations.

The purpose of the publication is not altogether clear. It is unlikely that a customer desiring information for design or planning purposes will require data for more than a small fraction of the stations included in this volume and his needs could possibly be met more economically by print-outs from computer data-banks. Further it is probable that the customer's real requirement is for further analysis of the data, for example frequency tables of values of temperature, or bivariate frequency tables covering temperature and humidity, wind direction and speed, etc.; such requirements are not met in this volume, despite its considerable size.

P. G. F. CATON

551.515.3

LETTER TO THE EDITOR

Comments on 'The tornadoes of 26 June 1973'

I agree with the conclusions of Mr Whyte¹—the storm of 26 June 1973 was undoubtedly 'a severe travelling storm of the wind-shear type'. As mentioned in his article, several other such storms have been observed in Great Britain. Furthermore, a number have been observed elsewhere in Europe, both by myself and by others—notably by the thunderstorm study group at the Atmospheric Physics Laboratory at the Swiss Federal Institute of Technology in Zürich (LAPETH, for short).

Nearly all severe storms occurring in Europe have the appearance of organized, travelling storms of the wind-shear type. Although exceptionally strong local convergence may cause a severe hailstorm to develop (see for example Staude²) such storms will be neither long-lasting nor organized. Of the 37 cases analysed thoroughly by Fenner,³ a few fell into this category, but most were organized storms of the type proposed observationally by Browning^{4,5} and theoretically by Moncrieff and Green.⁶ (The dynamics suggested by Newton⁷ are not supported by the substantially more rigorous work of Moncrieff and Green; his model must thus be revised.)

Mr Whyte noted the general absence of an environment characterized by a moist stable layer, with dry air above. The 37 cases cited above also show little evidence supporting such an air mass as 'typical' for Europe. Darkow⁸ and Miller⁹ noted that the 'typical tornado sounding' from the Pacific Northwest of the United States and Canada, a region far more similar to Europe than is the central area of the United States, does not contain an inversion. Soundings in Europe prior to severe local storm occurrences are similar to Miller's 'Pacific Northwest sounding'.

I also agree completely with all comments in Mr Whyte's first paragraph under 'Comparisons with similar situations' on pages 168-169; the main requirement for severe events accompanying thunderstorms is for the updraught to remain vigorous for comparatively long periods, i.e. to be 'steady'. Furthermore, the storm must have an organized downdraught, the importance of which is generally ignored! Without a vigorous, sustained downdraught, a storm cannot become an organized, travelling severe local storm.

There are three important interactions required before a thunderstorm evolves into a severe, organized, travelling storm: (a) between the updraught and downdraught in the 'mature' stage; (b) between the storm circulation and mesoscale circulation; and (c) between the storm and the wind shear. It is these three interactions which appear to cause organization.

It is common knowledge that severe storms characteristically move to the right of the path taken by 'non-severe' storms developing in the same area. After a storm becomes organized, it has an 'open' circulation (i.e. the environmental wind forms a part of the storm's circulation) and propagates continuously towards the direction which maximizes the kinetic energy of the low-level inflow air supply. The more common 'local' thunderstorms have a 'closed' circulation, i.e. it remains entirely within the storm.

In most cases, the low-level air entering the storm from upshear will have the greatest kinetic energy relative to the storm; in fact, in the 37 cases studied by Fenner, as well as the 26 June storm, the best predictor of severe storm movement was the mean wind-shear direction. On the contrary, for 'local' thunderstorms, which do not propagate continuously, the mean wind is the best forecast of movement.

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NOTES AND NEWS

Flood Studies Conference

A conference on Flood Studies will be held on 7–8 May 1975 at the Institution of Civil Engineers. The Flood Studies Report recently published by the Natural Environment Research Council will be considered, and authors and potential users will present papers discussing the results and their applications to practical problems. The Institution's draft manual on 'Floods in relation to reservoir practice' will be introduced and be open to discussion.

There will be six sessions at the conference, the first of which is expected to be chaired by Mr J. K. Bannon, Director of Services, Meteorological Office. Papers will be read by members of the Meteorological Office, the Institute of Hydrology, the Hydraulics Research Station, university departments and public water authorities.

Programmes and application forms may be obtained from the Conference Office, The Institution of Civil Engineers, Great George Street, Westminster, London SW1P 3AA.

Dial-the-weather Service for Lake District visitors

The Lake District National Park Information Service has installed an automatic telephone-answering system to cope with the hundreds of calls that it receives for weather information. Callers are now immediately connected to a recorded summary.

At first the service, specially provided in conjunction with the Main Meteorological Office, at Preston, covered conditions only at week-ends and on public holidays, but it is now being extended to become a full daily service.

At about 1630 an outlook for climbers and walkers is issued, covering the period from dawn to dusk on the following day; at about 0730 the next morning a more specific forecast is issued, covering all the usual weather elements.

The number to dial is Windermere 5151, and the service is being publicized through local newspapers and notices in hotels and guest-houses. The equipment used has an ultimate capability of accepting simultaneous calls on up to 10 Post Office lines, although initially only two lines have been in use.

Retirement of Mr J. Briggs

On 17 March 1975 Mr James Briggs retired from the Meteorological Office, where for the past three years he has held the post of Assistant Director, Special Investigations, having previously had an extremely varied career in both the Services and Research Directorates.

Mr Briggs joined the Office in May 1937 and after a short spell at the Training School at Croydon he was posted to Larkhill for sound-ranging duties. In September 1939 he was commissioned as a Flight Lieutenant in the Royal Air Force Volunteer Reserve and sent to France with the 1st Sound-ranging Battery, eventually being evacuated from Dunkirk in 1940. After a short spell in England he spent the rest of the war in North Africa and Italy, mainly as Senior Meteorological Officer at HQ 242 Group and at HQ 205 Group.

After demobilization in January 1946 Mr Briggs was posted as a Senior Scientific Officer to Dunstable where he served as an upper-air forecaster for seven years. On his promotion to Principal Scientific Officer in October 1953 he was posted as Senior Meteorological Officer to HQ 12 Group at Watnall, and at one time was in charge of 17 outstations.

In January 1961 Mr Briggs was moved to the Atmospheric Physics Branch, where he spent three and a half years doing research into clear-air turbulence. During this period several of his papers were published, one of the most interesting being concerned with wind-tunnel experiments using a model of the Rock of Gibraltar.

In July 1964 Mr Briggs was given a C.C. commission as Group Captain in the Royal Air Force and was posted as the Chief Meteorological Officer to SHAPE at Versailles, where he remained until the end of 1966. On his return he spent a short period in the Instruments and Observations Branch before joining the Special Investigations Branch. He became Head of this Branch on his promotion to Senior Principal Scientific Officer on 1 August 1972. During the last few years papers dealing with the probability of aircraft encounters with heavy rain and hail were among those written by Mr Briggs, and he has represented the Office on several national committees.

We all wish Mr and Mrs Briggs many years of happy retirement.

F. H. BUSHBY

HONOUR

The following honour was announced in the New Year's Honours List, 1975:

I.S.M.

Mr E. J. Crouch, Office Keeper I, OS4c, Meteorological Office Headquarters, Bracknell.

OBITUARIES

It is with regret that we have to record the death of Mr N. W. Baker, Scientific Officer, Met O 12 on 15 December 1974 and of Mr J. Kaye, Higher Scientific Officer, Watnall on 30 December 1974.

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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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AN EXPERIMENT TO DETERMINE THE VALUE OF SATELLITE INFRA-RED SPECTROMETER (SIRS) DATA IN NUMERICAL FORECASTING

By MARGARET J. ATKINS and M. V. JONES

Summary. An experiment was carried out in the Meteorological Office in March 1974 to evaluate SIRS as an operational source of data. As a result SIRS data are now available for use in the operational forecast, but are subject to scrutiny by the upper-air forecaster.

Introduction. In 1973 the United States of America announced that during the 12 months from June 1973 its weather ships would be withdrawn one by one from service at Ocean Weather Stations (OWS) 'B', 'C', 'D' and 'E' in the western Atlantic, and that the experimental Satellite Infra-red Spectrometer (SIRS) soundings would be transmitted operationally. It was therefore necessary to evaluate the SIRS data¹ (sometimes described as Vertical Temperature Profile Radiometer (VTPR) data) as an operational source of data.

An experiment was set up consisting of an additional forecast run in parallel with the operational forecast. In the experiment, satellite data were allowed to supplement conventional data in the numerical forecast suite. Use was made of data from 00 GMT on 7 March 1974 to 00 GMT on 15 March 1974.

The model used both operationally and for the experiment was the Bushby-Timpson 10-level primitive-equation model² in its two forms:

- (a) coarse-mesh over an octagonal area centred on the North Pole and tangential to about 15°N on a polar stereographic projection ('the octagon');
- (b) fine-mesh over a rectangular area (on the same projection) covering the North Atlantic and Europe ('the rectangle').

Both forms used the technique of quadric-fitting at grid points to provide objective analyses.^{3,4}

Organization of the experiments

(a) *General remarks.* In spite of the large amount of computer time involved in running an experimental forecast suite for each 12-hour datum time over a period, the experiment was run in 'real time' to avoid problems of recovering data from an archive, and to enable more realistic intervention to be effected (see below).

The programs that provided analyses of geopotential height and humidity over the octagon and rectangle were made flexible, so that the choice of data to be used was controlled externally. Thus both program suites automatically used the same method of analysis and were therefore directly comparable. However, some effort was required in advance to ensure that the octagon and rectangle versions of the height analysis were compatible, particularly in the method of incorporating SIRS data.

Each analysis program needs a 'background field', which is a first guess at the analysed field. It is normally a 12-hour forecast from the previous update run (see below). In the experimental suite it was necessary to use the same background fields of height and humidity as in the operational suite for the first datum time, but thereafter each suite produced its own background fields. Thus there was a 'run-up' period of about two days during which the effect of satellite data was allowed to become fully established in the experiment.

(b) *Intervention.* In the operational suite, incoming data are read from paper tape, and at fairly frequent times of the day a 'data bank' is updated with the most recently received data. Before the height and humidity analyses are made, a set of 'Basic Analysis Data Sets' (BADs) is compiled from the current data bank for both octagon and rectangle. In order to justify comparison of the suites, it was necessary to arrange identical cut-off times for the data. This requirement was satisfied most readily by starting the experiment from the set of operational BADs, since decisions about inclusion or exclusion of types of data could be made during the height and humidity analyses.

Such an arrangement means that all intervention except the addition of artificial observations (also known as 'bogus' observations) will have been effective by the time the BADs are produced. Therefore any difference of intervention between the suites must be carried out in the form of bogus observations.

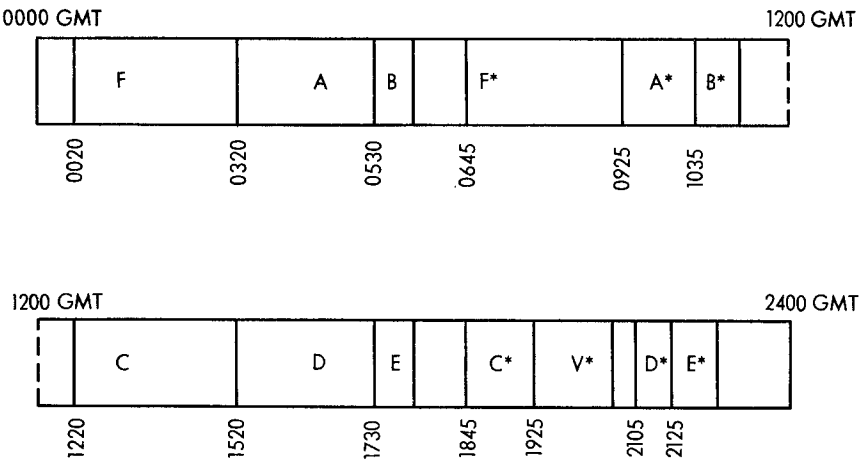
For the period of the experiment an extra roster of forecasters was on duty in the Central Forecasting Office (CFO) at Bracknell, to provide bogus intervention appropriate to the experiment. The intervener could use as much SIRS information as he could acquire, whether or not it had been included in the BADs. He was provided with machine-plotted charts appropriate to the experiment, and of course the computer output from the experiment itself. The operational forecaster was not allowed access to any SIRS information.

(c) *The program suites.* In the remainder of this paper, the adjective 'main' refers to runs with a data cut-off time of 0300 or 1515 GMT, whereas 'update' refers to runs with a cut-off time of 1200 or 0000 GMT. The purpose of the update run is to introduce into the model all the appropriate data that have been received since the main-run cut-off time. The influence of these data is indirect, since the forecast is taken to 12 hours only, and is used to provide background fields for the height and humidity analyses of the next main run.

In order to reduce demand on the computer resources for the experiments, full 72-hour (octagon) and 36-hour (rectangle) main forecasts were made using

only midnight data. However, a complete cycle of main and update runs was necessary for octagon and rectangle, but the runs based on midday data were considerably shortened, and the requirement for output was considerably less than in the operational suite. The arrangement of the running of the suites in real time is depicted in Figure 1. The timing of the runs was chosen to enable the forecaster to intervene under pressure similar to that experienced on the operational bench, although in practice that pressure was difficult to achieve.

(d) *Assessment of results.* The forecasts were assessed both subjectively and objectively. The objective assessment made use of a verification scheme essentially similar to that used in the octagon operational suites, although special



Definitions of A—F, A*—F*and V*

Run	Operational	Experimental
Midnight main octagon	A	A*
Midnight main rectangle	B	B*
Midnight update octagon and rectangle	C	C*
Midday main octagon	D	D*
Midday main rectangle	E	E*
Midday update octagon and rectangle	F	F*
Verification and preservation of results		V*

FIGURE 1—ARRANGEMENT OF RUNS IN REAL TIME DURING THE EXPERIMENT

provision had to be made for use over a limited period. Forecasts made during the 'run-up' period were not verified. Furthermore, in order to verify the forecasts from the final datum time, special programs were run for three days from the end of the experiment (the 'run-down' period). Also included were programs to verify the operational forecasts over the same period, for comparison with the experiments.

Objective verification of rectangle rainfall forecasts will be described in a later paragraph.

Synoptic situation 9–15 March 1974. The first part of the period of the experiment began with high pressure over Scandinavia with a ridge extending over the British Isles, lower pressure over northern France, and a deep depression in the west Atlantic between Newfoundland and Greenland. Small lows moved round the main depression and some broke away and ran into northern France and southern Britain. These were fairly shallow features with small amounts of rain and they dissipated as they moved towards the main high. A similar pattern was reflected in the upper air with troughs moving round the Atlantic low and ridges building between them. A cut-off 500-mb low remained over the British Isles until 14 March. The region of high pressure moved slowly eastwards, leaving a cut-off high near Iceland. On 14 March the block broke down and a secondary low running round the old west-Atlantic low became dominant, deepened and ran forward across the British Isles with associated belts of rain. This was associated with the eastward extension to the south of Iceland of an upper trough from the old west-Atlantic low and the return of westerly flow over the southern part of the British Isles. Figure 2 is reproduced from *Weather Log* for March 1974 (published by the Royal Meteorological Society) and shows the sequence of midday hand-drawn analyses for the period.

Subjective assessment. The assessment began with forecasts based on data for 00 GMT, 9 March 1974, that is to say, after the run-up period. The area considered in the subjective assessment was centred on the British Isles and included parts of western Europe and the eastern Atlantic. The rectangle forecasts of 500-mb height, surface pressure and rate of rainfall were assessed at 12-hourly intervals and the octagon forecasts of surface pressure and 500-mb height were assessed at 24-hourly intervals. In addition the surface-pressure and 500-mb analyses were assessed for each area. A combined mark was given for each forecast and a separate mark was given for the surface and 500-mb analyses according to the following scale:

- A Experimental run (including the SIRS data) significantly better than the operational run.
- B Experimental run better than the operational run.
- C Experimental run and operational run equally good.
- D Experimental run worse than the operational run.
- E Experimental run significantly worse than the operational run.

('Significant' in categories 'A' and 'E' implies that a forecast issued on the basis of the computer prognosis would be different. Categories 'B' and 'D' indicate that some differences were found in the computer prognoses but that these would not have affected an issued forecast.) In addition there was a

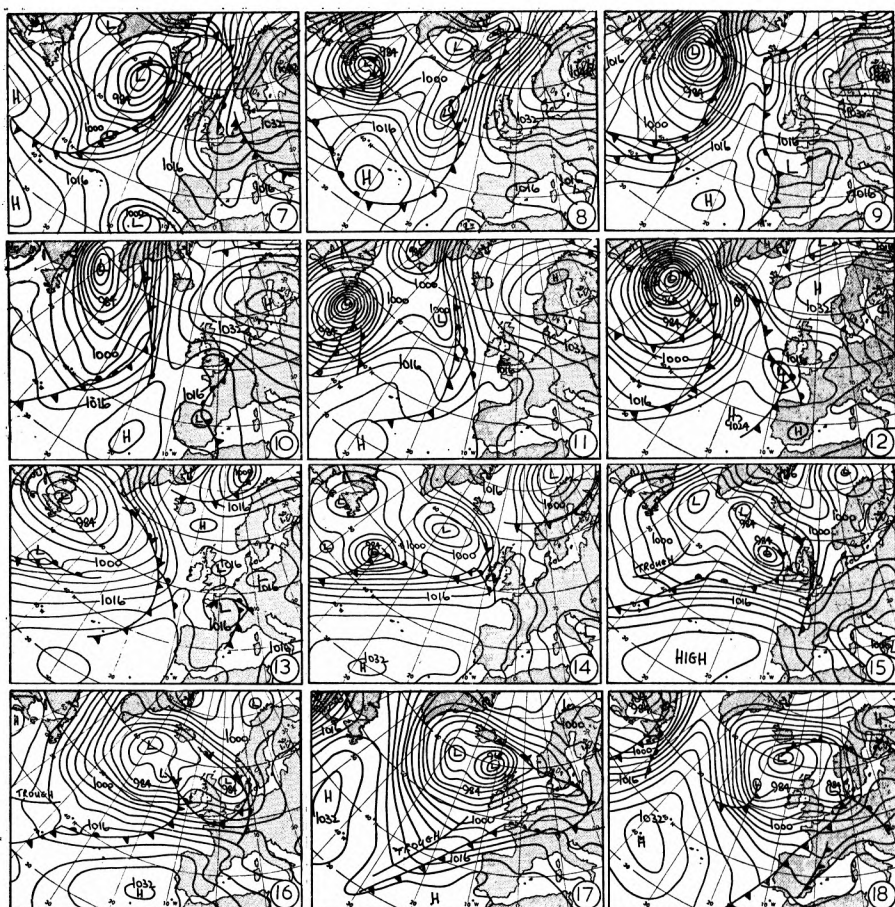


FIGURE 2—DAILY WEATHER MAPS FOR 12 GMT, MARCH 1974

Dates are ringed at the lower right-hand corner of each map.
Mean-sea-level isobars are drawn at intervals of 4 millibars.

category 'X' used for analyses only, which implied that the charts were different but that owing to the lack of conventional data it was impossible to decide which was the better. The results of the subjective assessment for individual days are shown in Table I and a summary is shown in Table II.

As can be seen from Table II there were no 'A' or 'E' marks. This means that on no occasion would the forecast of weather issued for the British Isles have been affected by the inclusion of satellite data. For most comparisons, especially of forecasts for a period of more than 24 hours, the predictions were closer to each other than to the actual situation. In particular, as indicated by the annotation in Table I, none of the forecasts predicted the change of type to westerly conditions which occurred on 14 March. It is interesting to note that the octagon forecast based on 00 GMT, 14 March gave the largest reduction in root-mean-square 500-mb height error when SIRS data were included (see Figure 3). The forecasts were assessed subjectively as equally good because although they were different from each other they were equally misleading.

TABLE I(a)—RESULTS OF SUBJECTIVE ASSESSMENT—OCTAGON

Data time 00 GMT	Analysis		$T + 24$	$T + 48$	$T + 72$	Number of SIRS in analysis area
March 1974	Surface pressure	500-mb				
9th	D*	C	D	D	B	43
10th	C	C	B	B	B	53
11th	C	B	B	C	C	102
12th	B*	C	B	B	C†	30
13th	C	C	C	B	B	16
14th	C	X	C†	C†	C†	120
15th	C	C	D	C	C	62

TABLE I(b)—RESULTS OF SUBJECTIVE ASSESSMENT—RECTANGLE

Data time 00 GMT	Analysis		$T + 12$	$T + 24$	$T + 36$	Number of SIRS in analysis area
March 1974	Surface pressure	500-mb				
9th	D*	C	B	C	C	2
10th	C	C	C	C	B	15
11th	C	C	C	B	C	16
12th	C	X	B	B	C	14
13th	C	C	C	C	C	5
14th	C	X	B	B†	C†	34
15th	B	D	D	D	C	11

* Due to pre-intervention.

† Both forecasts poor.

For explanation of letters see page 128.

TABLE II—SUMMARY OF THE RESULTS OF THE SUBJECTIVE ASSESSMENT SHOWING THE NUMBERS OF ASSESSMENTS IN EACH CATEGORY DERIVED FROM TABLE I

(a) Octagon

Category	Analysis		$T + 24$	$T + 48$	$T + 72$	Total from forecasts	Percentage of forecasts
	Surface	500-mb					
A	0	0	0	0	0	0	0
B	1	1	3	3	3	9	43
C	5	5	2	3	4	9	43
D	1	0	2	1	0	3	14
E	0	0	0	0	0	0	0
X	0	1					

(b) Rectangle

Category	Analysis		$T + 12$	$T + 24$	$T + 36$	Total from forecasts	Percentage of forecasts
	Surface	500-mb					
A	0	0	0	0	0	0	0
B	1	0	3	3	1	7	33
C	5	4	3	3	6	12	57
D	1	1	1	1	0	2	10
E	0	0	0	0	0	0	0
X	0	2					

For explanation of letters see page 128.

Considering the above points and bearing in mind that the results on some occasions were influenced by different 'pre-intervention' (that is, intervention before the main-run analysis, see Table I) it is nevertheless true that on the whole the inclusion of satellite data was beneficial. This is particularly noticeable for the octagon forecasts which were better for 43 per cent of forecasts when satellite data were included. On many occasions when a 'C' marking was given there was, in fact, a slight improvement when SIRS data were included, whereas the reverse was true on very few occasions.

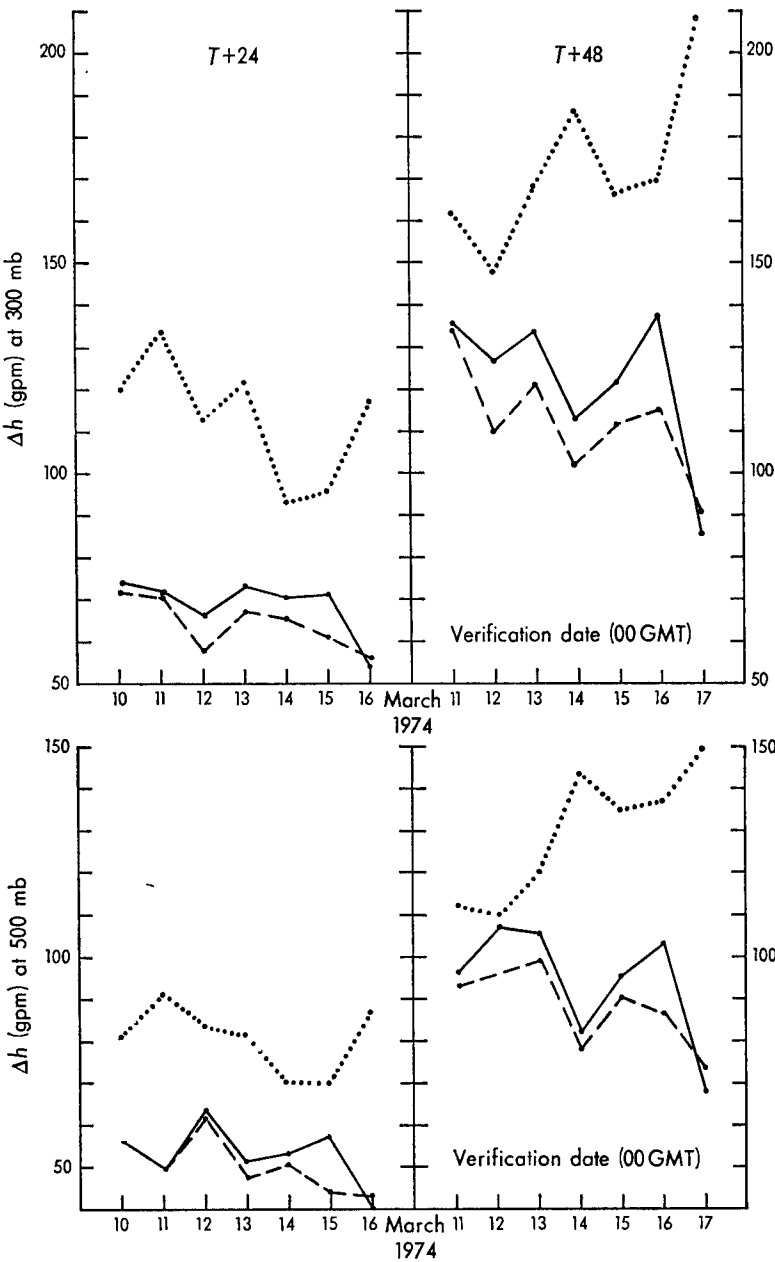


FIGURE 3—ROOT-MEAN-SQUARE DIFFERENCES, Δh , BETWEEN FORECAST AND OPERATIONAL UPDATE-RUN ANALYSED HEIGHTS FOR 24-HOUR AND 48-HOUR FORECASTS AT EACH 00 GMT VERIFICATION TIME

Top: 300 mb Bottom: 500 mb
●—● operational ●---● experimental ●...● persistence

There were only two occasions when the forecast without satellite data was marked as better. The first was 00 GMT, 9 March 1974. In this case the operational forecast was better owing to better pre-intervention. The second was 00 GMT, 15 March 1974, which is discussed separately below.

Objective assessment of octagon forecast. Objective verification of the experiment made use of two basic comparisons:

- (a) Forecast fields against operational update-run analysed or initialized fields appropriate to the verification time.
- (b) Forecast fields against values observed at various stations at the verification time.

The 'forecast fields' referred to are of three kinds: one from the experiment, one from the operational suite, and, as a control, 'persistence', in which observed, analysed or initialized values are maintained throughout the forecast period.

In the comparison of forecast and analysed fields, the region used was a rectangular array of 560 points covering most of Europe, the Atlantic, most of Canada, and the north-east U.S.A. (see Figure 4). In the comparison of forecast fields with observations, two groups of stations are used: one of 28 stations in north-west Europe, the other of six mid-Atlantic stations (see Table III). The latter group is clearly more prone to influence from a single station, so that caution is necessary when considering its statistics.

TABLE III—OBSERVATIONS USED IN OCTAGON VERIFICATION

(a) 28 Stations in Europe and their international station numbers					
01415	Stavanger	03953	Valentia	07645	Nîmes
02084	Göteborg	06011	Thorshavn	10035	Schleswig
03005	Lerwick	06181	København	10338	Hannover
03026	Stornoway	06260	De Bilt	10384	Berlin
03170	Shanwell	06447	Uccle	10739	Stuttgart
03322	Aughton	06610	Payerne	10866	München
03496	Hemsby	07110	Brest	12330	Poznań-Lawica
03774	Crawley	07145	Trappes	16080	Milano
03808	Camborne	07480	Lyon		
03920	Long Kesh	07510	Bordeaux		
(b) 6 Atlantic Stations					
04018	Keflavík	OWS 'B'		OWS 'J'	
04270	Narssarssuaq	OWS 'I'		OWS 'K'	

Forecasts against analyses (octagon)

(a) *Accumulated statistics.* Table IV is a summary of the accumulated statistics for 12-, 24- and 36-hour height forecasts from the two suites over the period of the experiment, excluding the run-up and run-down periods. The effect of SIRS observations is in general a beneficial one, according to Table IV, at all levels except 100 mb. At this level raw SIRS thickness data (adjusted only by addition of a 1000-mb analysed value) have an inherent roughness which is reduced at lower levels by a correction based on the 100-mb random error.³

(b) *Daily statistics—height errors.* Figures 5(a) and 5(b) represent comparisons of the progress of each individual forecast at 200 mb and 500 mb in terms of root-mean-square (r.m.s.) height differences between the forecast and the operational-update analysis at the verification time. If forecast periods of less

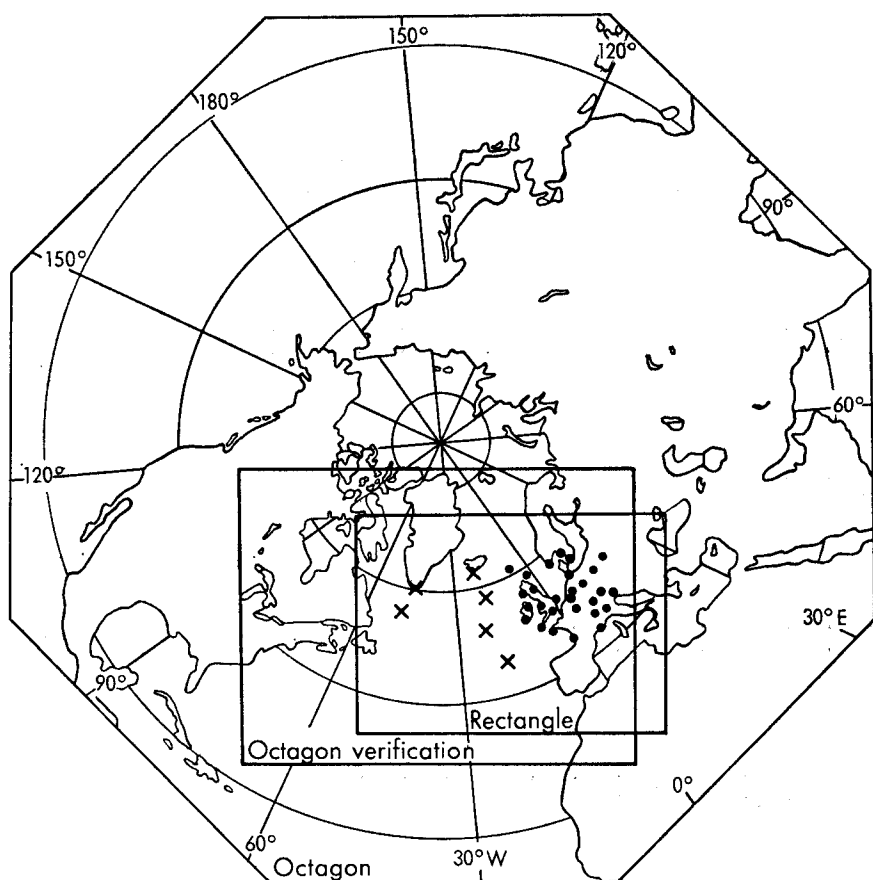


FIGURE 4—10-LEVEL MODEL REGIONS

Octagon 3037 grid points

Rectangle 3072 grid points

Verification region 560 grid points

● 28 upper-air stations (Europe)

× 6 upper-air stations (Atlantic)

Partial latitude circles are shown at 20°, 40°, 60° and 80°N.

than 24 hours are ignored for the present it can be seen that all the experimental forecasts have lower r.m.s. height differences than the corresponding operational forecasts, with the exception of the last. In the earlier part of each of the 500-mb forecasts, the experimental one has larger errors (except for one day), whereas at 200 mb the reverse is the case, with the final day again being an exception.

Figure 3 compares equal-period forecasts of height from the experiment, the operational suite and persistence, on a daily basis for two levels. Again they show that on every occasion except the last the experimental forecast was slightly less in error than the operational forecast and that both were considerably better than persistence.

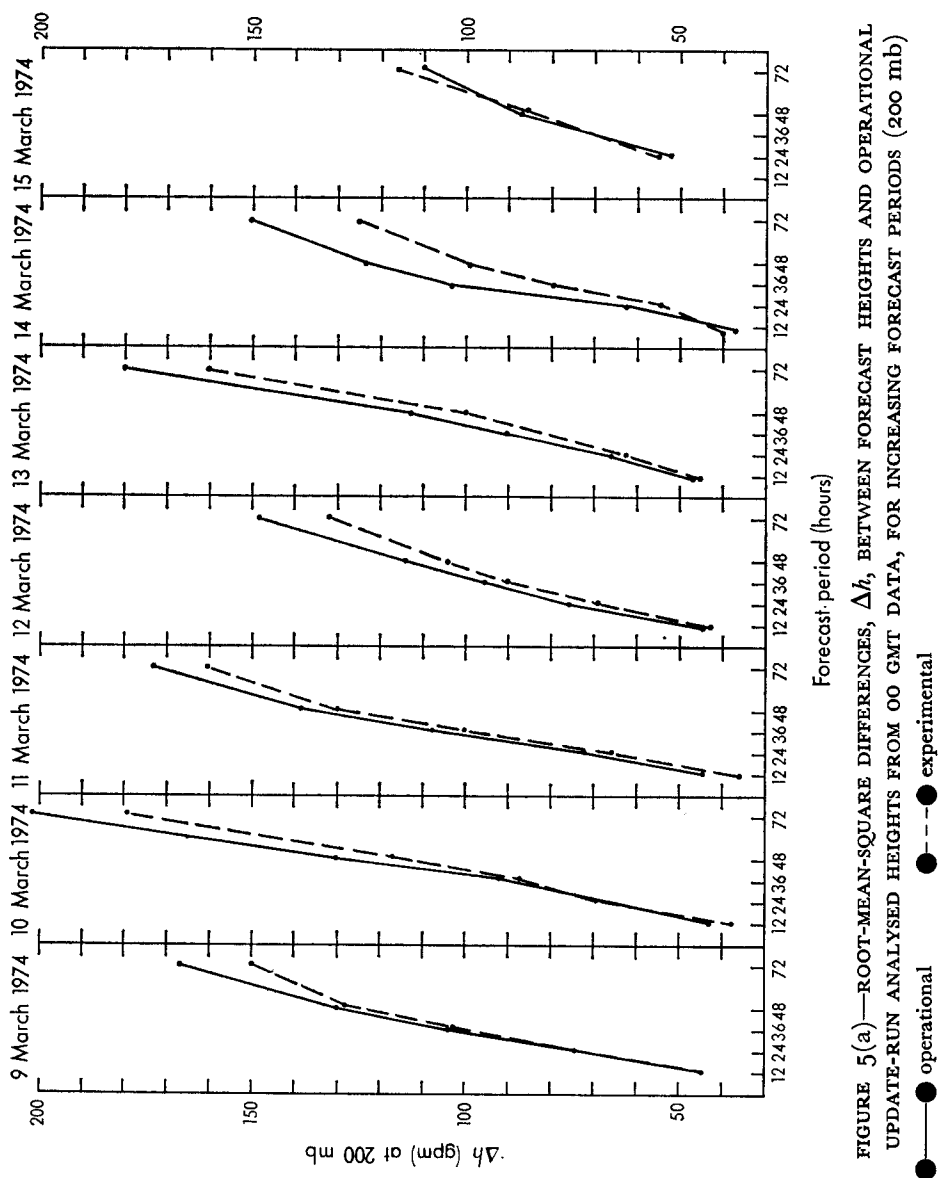


FIGURE 5(a)—ROOT-MEAN-SQUARE DIFFERENCES, Δh , BETWEEN FORECAST HEIGHTS AND OPERATIONAL UPDATE-RUN ANALYSED HEIGHTS FROM 00 GMT DATA, FOR INCREASING FORECAST PERIODS (200 mb)

—●— operational - - - ● - - - experimental

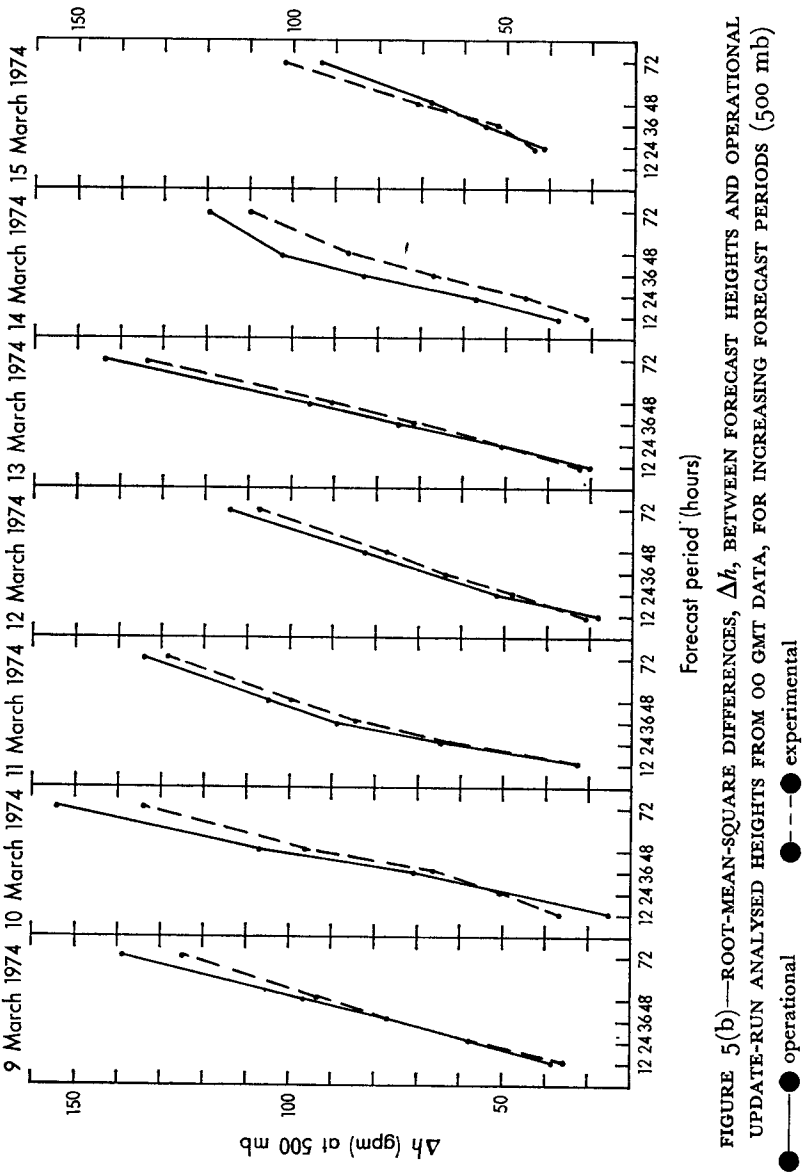


FIGURE 5(b)—ROOT-MEAN-SQUARE DIFFERENCES, Δh , BETWEEN FORECAST HEIGHTS AND OPERATIONAL UPDATE-RUN ANALYSED HEIGHTS FROM 00 GMT DATA, FOR INCREASING FORECAST PERIODS (500 mb)

(c) *Daily statistics—wind errors.* Figures 6(a), 6(b) and 6(c) represent comparisons of persistence, operational and experimental mean vector-wind errors for 24-, 48- and 72-hour forecasts respectively at two levels. The values plotted are of the mean vector departure of the forecast wind from the operational update-run initialized wind at verification time. An organizational error caused the statistics for a verification time of midnight on the 15th to be invalid, so these statistics have not been presented.

In general Figure 6 shows that the experiment usually produces a very slight improvement on the operational forecast. Figure 6(c) shows further that in the relatively static synoptic situation at the beginning of the period a 72-hour persistence forecast was better than either the operational or the experimental 72-hour forecast. It is probably unwise to make any more-detailed inferences, in view of the wide variability displayed by the curves.

TABLE IV—OCTAGON 10-LEVEL MODEL VERIFICATION, 00 GMT ON 9 MARCH TO 00 GMT ON 15 MARCH 1974 (ACCUMULATED STATISTICS)

Forecast	Number of cases*	1000 mb Root-mean-square metres between forecast and objective analysis†	500 mb height differences in geopotential	300 mb	200 mb	100 mb
$T + 12$ Experimental†	12	25	30	40	40	51
Operational†	12	25	30	39	40	49
$T + 24$ Experimental	6	43	52	65	66	89
Operational	11	45	55	69	70	89
$T + 36$ Experimental	5	59	73	87	92	127
Operational	10	62	76	97	97	123

* Experimental 24- and 36-hour forecasts are available only for midnight data, whereas the midday forecasts are included in the operational statistics and also in the 12-hour experimental statistics.

† All $T + 12$ forecast statistics are based on update runs. The update-run objective analysis at the verification time is used for the comparison.

Forecasts against observations (octagon). Table III(a) is a list of the 28 European stations whose observations are used in the comparison, and their positions are plotted as dots in Figure 4.

As a guide to the effect of SIRS data on forecasts of jet speed, Figure 7 shows a comparison of daily 300-mb r.m.s. vector-wind errors. The experimental and operational curves are very similar for both 24-hour and 48-hour forecasts, with the exception once again of the end of period.

Since the withdrawal of observations at OWS 'C' and 'D', there is a very poor network of stations available for a similar comparison in the Atlantic area. Such a comparison was in fact made, using the six stations of Table III(b), but the results were unrepresentative and are not reproduced here.

Objective verification of rainfall (rectangle). Rainfall accumulations were verified for the 14 areas shown in Figure 8 for the forecasts based on data for the period from 00 GMT, 9 March to 00 GMT, 15 March 1974. An average rainfall was calculated for each area for the 12- to 24-hour and 24- to 36-hour periods of both the operational and experimental forecasts. These were verified against actual average values obtained for the same areas from rainfall data from synoptic stations.

The results, illustrated in Tables V and VI, show very little difference between the two forecasts. Certainly they show that forecasts including satellite data were no worse than those without. Table V shows the accuracy of the forecasts

in distinguishing between wet and dry periods. For accumulations over the 24-hour period from 12 to 36 hours the two forecasts were identical; for the two 12-hour periods 12 to 24 and 24 to 36 combined, the forecasts including satellite data were marginally better. This indicates that the experimental forecasts were slightly better at timing the rain than the operational forecasts, but the differences are insignificant especially in view of the errors in deriving areal mean values from relatively sparse actual rainfall data. Table VI compares the sum of the forecast values for each area for both forecasts with the sum of the actual mean values. This comparison shows that except for the forecast beginning at 00 GMT on 15 March 1974 there were no significant differences in the total rain predicted by the two forecasts, the forecasts including satellite data being marginally better. For 00 GMT on 15 March, there was a significant decrease in the amount of rain predicted when satellite data were included. The experimental forecast appears to be the better in this case.

It is unfortunate that there was only one occasion (15 March) during the experiment when there was a belt of widespread frontal rain in the verification area and therefore the results do not give any reliable information about the effect of satellite data on forecasting similar frontal situations with widespread moderate or heavy rain.

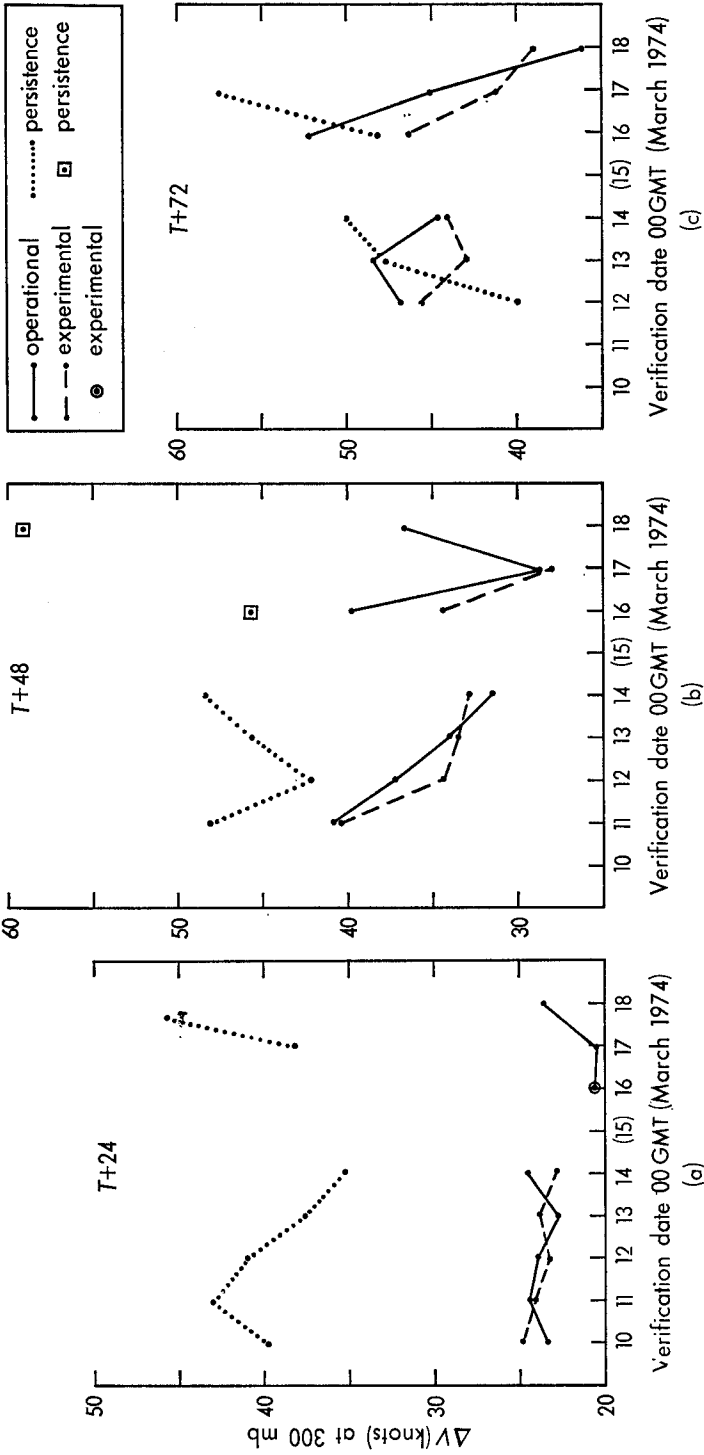
TABLE V—2 × 2 CONTINGENCY TABLE FOR WET AND DRY PERIODS, COMBINING ALL THE AREAS DEPICTED IN FIGURE 8

(a) All 12-hour periods $T + 12$ to $T + 24$ and $T + 24$ to $T + 36$							
		Operational				Experimental	
Actual	DRY	DRY	WET	Actual	DRY	DRY	WET
	WET	57	16		WET	58	15
		40	83		39	84	
(b) All 24-hour periods $T + 12$ to $T + 36$							
		Operational				Experimental	
Actual	DRY	DRY	WET	Actual	DRY	DRY	WET
	WET	23	6		WET	23	6
		21	48		21	48	

TABLE VI—DAILY TOTALS OF THE MEAN VALUES OF ACCUMULATED RAIN (IN MILLIMETRES) IN EACH OF THE 14 AREAS SHOWN IN FIGURE 8

Data time 00 GMT	Verification period $T + 12$ to $T + 24$			Verification period $T + 24$ to $T + 36$		
	Actual	Without SIRS	With SIRS	Actual	Without SIRS	With SIRS
March 1974						
9th	3	3	3	8	2	2
10th	12	4	5	9	4	4
11th	8	7	7	9	7	8
12th	15	6	6	15	5	6
13th	9	6	6	8	10	8
14th	14	9	9	28	9	10
15th	24	41	30	17	26	18

The last forecast. The octagon forecast from a datum time of 00 GMT on 15 March 1974 (which was the last datum time of the experiment) has been mentioned several times as being exceptional. The subjective assessment of the rectangle forecasts for the same datum time also indicated that the experimental forecast was worse up to 24 hours (Table I(b)). Some explanation is therefore required.



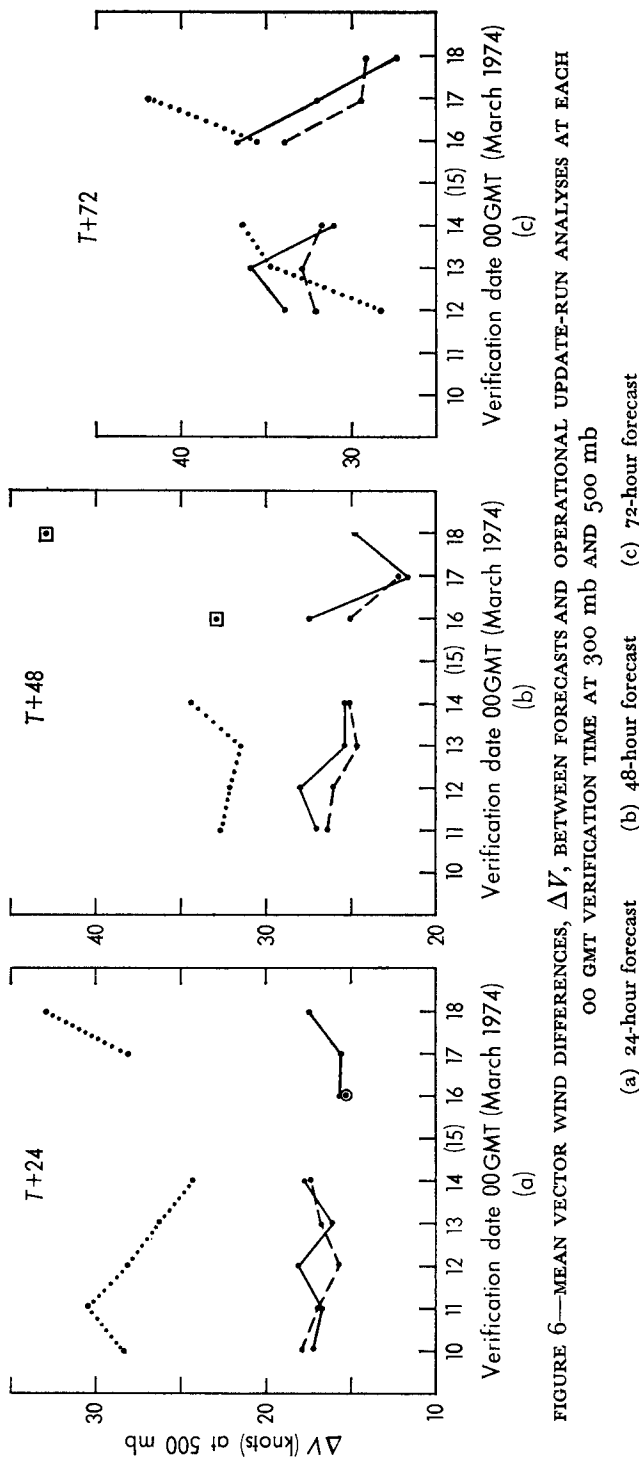


FIGURE 6—MEAN VECTOR WIND DIFFERENCES, ΔV , BETWEEN FORECASTS AND OPERATIONAL UPDATE-RUN ANALYSES AT EACH 00 GMT VERIFICATION TIME AT 300 mb AND 500 mb

An organizational error invalidated the statistics for a verification time of 00 GMT on 15 March and also invalidated the statistics for persistence forecasts from that time.

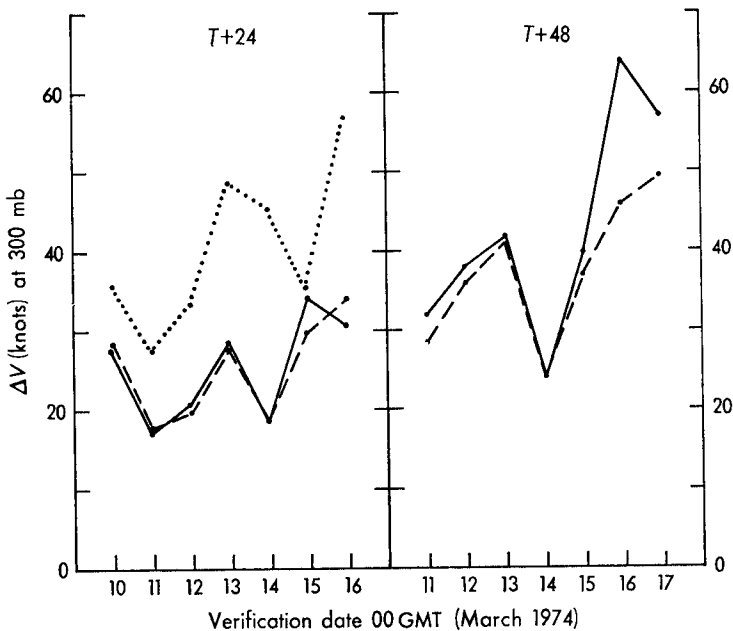


FIGURE 7—MEAN VECTOR WIND DIFFERENCES, ΔV , BETWEEN 300-mb FORECASTS AND OBSERVATIONS AT EACH 00 GMT VERIFICATION TIME FOR 24-HOUR AND 48-HOUR FORECASTS

The 28 European stations whose observations were used for this comparison are listed in Table III(a).

●—● operational ●— — ● experimental ● . . ● persistence (24-hour only)

In spite of a better background field, the experimental rectangle 500-mb analysis was poorer, owing to erroneous rejection of 400-mb and 500-mb wind observations from OWS 'I' which were retained by the operational rectangle analysis. (These winds were rejected by both the octagon analyses.) It is worth noting at this point that *both* rectangle analyses wrongly rejected the 300-mb wind and 1000–500-mb thermal wind at OWS 'I'. The wind rejection scheme (which compares an observed wind with the corresponding interpolated wind from an analysis of unchecked data) can occasionally reject a crucial observation, as it appears to have done here. (The method of applying quality-control checks to wind observations is under study in connection with the orthogonal-polynomial method of analysis.)

On the 14th and 15th the blocking anticyclone which had dominated northern Europe declined, allowing a brief period of westerlies to develop. Figures 3 and 7 show a tendency towards peaks in the error curves for the penultimate octagon case, which could therefore be rated as a relatively poor forecast, as might be expected when a blocking situation suddenly subsides. However, it is for this penultimate case that the improvement in the forecast due to the inclusion of SIRS data in the analysis is greatest.

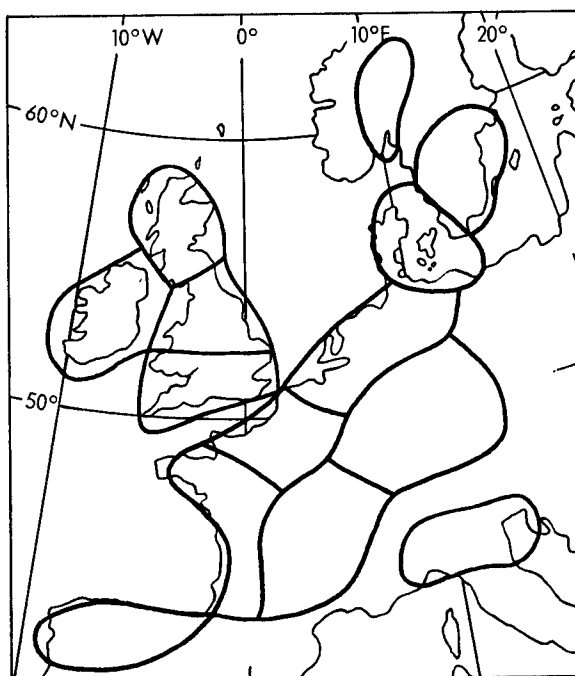


FIGURE 8 —AREAS OVER WHICH RAINFALL WAS AVERAGED FOR OBJECTIVE VERIFICATION

It is therefore difficult to explain why the last case of all should give worse octagon forecasts in the experiment. One possibility is that the SIRS data are of poorer quality in this situation, based as they are on Washington National Meteorological Center (WNMC) *forecast* temperature profiles. If the WNMC forecast was a poor one (as was ours) at the cessation of a blocked situation, then that would be reflected in the quality of the SIRS observations as transmitted. The 48-hour forecast issued by WNMC, based on 00 GMT data for 14 March, has been assessed by CFO as relatively poor near the United Kingdom (compared with the previous and subsequent forecasts). This may be an indication that shorter-period forecasts based on the same data were also relatively poor, in which case the above hypothesis is supported.

Conclusion. Both the objective and subjective assessments of the coarse and fine-mesh forecasts show that in general the inclusion of satellite data in the objective analyses produced small beneficial effects on the forecasts in the region of the British Isles and North Atlantic during the period of the experiment. For the majority (57 per cent) of fine-mesh forecasts, the results were similar or very slightly better when satellite data were included and for about one-third of the forecasts there was a distinct improvement; 43 per cent of the coarse-mesh forecasts showed a distinct improvement. Except for one occasion (00 GMT on 15 March 1974) the inclusion of satellite data did not have any harmful effects, and on that occasion they did not produce any serious errors.

The experiment indicated that the operational use of SIRS data would on the whole be beneficial and would not produce any worsening of the forecasts.

As a result SIRS data were incorporated into the operational objective analysis on 26 March 1974. In view of the larger numbers of SIRS data to be examined by the upper-air forecaster facilities have been introduced for rejecting not only individual SIRS observations but also all SIRS, or all SIRS within particular limits of latitude, longitude and pressure level. The operational use of satellite data showed that they were unsatisfactory in low latitudes, and on 9 April 1974 the octagon analysis was modified to reject automatically all satellite data south of 25°N. It is hoped that continued experience in using SIRS data operationally will lead to improved methods of incorporating them into objective analyses and that in the long term, as their quality improves (as one hopes it will), careful monitoring will ensure that the best use is made of them.

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ESTIMATES OF THE PROBABILITY OF OCCURRENCE OF HIGH RATES OF SNOWFALL

By R. N. HARDY

Summary. A method of assessing the likelihood of high rates of snowfall at stations for which lengthy autographic records are available is described, and results are presented for some stations in the United Kingdom.

Introduction. For some design purposes there is a need to specify the probability levels for the occurrence of high snowfall rates. It is not sufficient, even if it were possible, to estimate an all-time extreme value, for the penalties (in weight, cost or efficiency of the equipment being considered) involved in coping with such an unlikely event may be prohibitive.

This note describes an attempt to solve the problem by means of a computer analysis of statistics of hourly rainfall amounts (in tenths of a millimetre) and durations (in tenths of an hour) compiled for several years from autographic rain-gauge records at a number of U.K. stations.

The analysis scheme. Because of difficulties of measurement there is little direct information on rates of snowfall. The Meteorological Office tilting-siphon rain recorder used at main observing stations includes a small heater (25-watt lamp) for frost protection, so that rates of sleet* and slight snow at near freezing point may be measured to a good approximation. However, large rates of fall of frozen precipitation over short periods cannot be determined accurately even by the most skilled and dedicated observer.

The total precipitable water in the atmosphere at a particular place has been found¹ to be highly correlated with the surface dew-point which, when precipitation is falling, is itself closely related to the surface air temperature. This explains why there is a fairly well-defined, although not large, decrease with surface temperature in the proportion of precipitation falling at high rates, except at the temperature extremes which probably mostly correspond to clear anticyclonic conditions. For example, Figure 1 shows a family of histograms for London/Heathrow Airport, each covering all temperature ranges for the 23 years up to 1971. From the left-hand side it gives the percentage time during which the temperature lay within each 2.5-degree Celsius band, the percentage of those times during which rain fell at 0.1 mm/h or more and then percentages of the latter times during which rates of from 2 to 25 mm/h were exceeded. The increasing bias towards high temperatures can be clearly seen. It is possible in view of this to consider rainfall-rate statistics for a temperature band wherein it is known that a large proportion of the precipitation will have fallen as rain, and to argue that this represents an upper envelope for snowfall rates. This is the approach adopted here.

The basic data used comprise rainfall amounts recorded over fixed one-hour periods and the rainfall duration within each hour to the nearest tenth of an hour. Intensities are calculated from these, and the question arises whether or not this masks fluctuations which are sufficient to cause high-intensity rainfall durations to be significantly understated. A good deal of work has been done on relating the variation in duration of rainfall at different rates with the averaging period used. Unfortunately this has primarily been concerned with relating clock-hour averages of convective high-intensity rain with instantaneous (2-minute) intensity distributions (see, for example, Briggs and Harker²) whereas the durations used here are resolved to the nearest 6 minutes, and frontal-type precipitation is the main concern. Furthermore, since snowflakes, unlike raindrops, show little change in terminal velocity with size, snowfall cannot be expected to display the same degree of short-period variability as rain. An investigation by Dyer³ supports this conclusion: she measured the fluctuation of snowfall rates during 15 Montreal snowstorms by using optical instruments operating over a 71-metre path, roughly equivalent to 2½-minute averaging. The rate of fall was found to be essentially a simple Markov process, with a small-amplitude random component superimposed. Power spectra showed a strong low-frequency component, falling off steeply above 4 cycles per hour. It seems reasonable therefore to expect the degree of distortion introduced in the present analysis by the averaging to be small.

Data were considered for 23 locations in the United Kingdom over periods ranging from 6 to 23 years, 376 years in all. Initially frequency distributions

* The term sleet is commonly used in this country to describe precipitation of snow and rain (or drizzle) together, or of snow melting as it falls, but it has no agreed international meaning.

London/Heathrow Airport 1949—71 inclusive

- A Percentage of time with temperature in given ranges.
- B Percentage of A for each temperature band with precipitation exceeding 0.1 mm/h.
- C—H Percentage of B for each temperature band with precipitation exceeding 2, 5, 10, 15, 20, and 25 mm/h respectively.

Note the changes of vertical scale.
For details of data used see text.

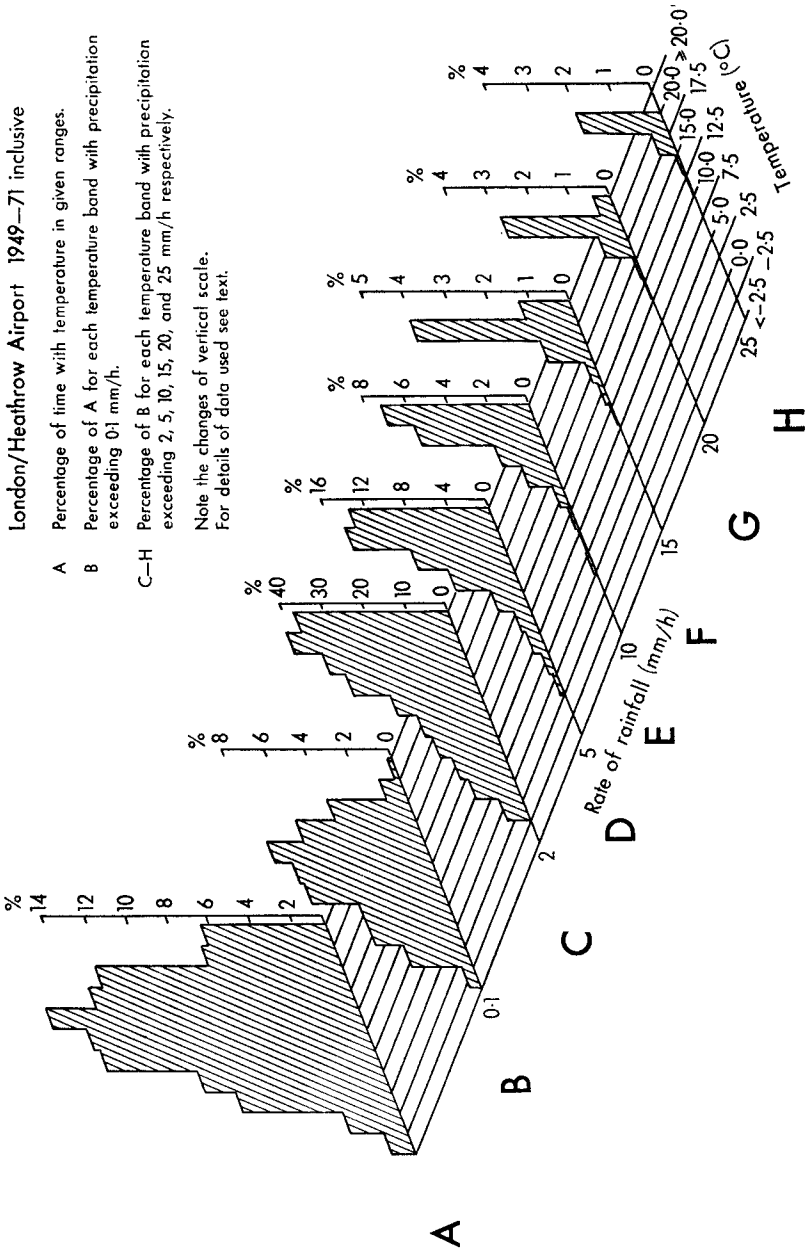


FIGURE 1—AN EXAMPLE TO SHOW THE DECREASE WITH DECREASING TEMPERATURE IN THE PROPORTION OF PRECIPITATION FALLING AT HIGH RATES

of the duration of precipitation at various rates were computed for each 2.5-degC temperature band from -10° to $+20^{\circ}$ C for each station. The expected decrease with temperature in the proportion of precipitation falling at high rates was evident at all stations. Small amounts of precipitation were reported at temperatures well below 0° C and, although their accuracy as regards rates of fall must be regarded with caution, it was considered that they should be included. It appeared that 2.5° C was a suitable upper temperature threshold, because then a large proportion of the precipitation considered would certainly have fallen as rain, whilst most sleet, almost all snow and a little hail would also be included. Hence percentages of precipitation exceeding various rates with air temperature less than 2.5° C were computed for each station. The few periods of precipitation at very high rates were individually checked against the reported weather, and cases of ice pellets or graupel were excluded. This is because the processes of formation differ from those of snow so that the two are in no sense interchangeable. To be fully consistent, rain from convective cloud should also have been excluded, but because such a very small part of precipitation at temperatures below 2.5° C falls as rain showers such refinement is not essential.

Results. The cumulative percentages for each station were plotted on logarithmic graph paper and straight lines fitted by eye. In all cases the fit was quite good—indeed the three largest departures were found to be data errors when checked against the original records; examples are given in Figure 2 for London (Heathrow), Edinburgh (Turnhouse), Cardiff (Rhoose), Belfast (Aldergrove) and Lerwick. From the set of curves, rates of precipitation exceeded for 1 per cent and 0.1 per cent of the time were read off. These values are listed in Table I and plotted in Figure 3; they are considered to represent realistic if slightly exaggerated estimates of rates of snowfall likely to be encountered within the lowest few hundreds of feet, for the given percentages of the time that the surface temperature is below 2.5° C and precipitation is falling at a rate of 0.1 mm/h or more. The isopleths in Figure 3 must be regarded as largely speculative, though the broad minimum over central England, coastal maxima and local maximum south-east of the Cheshire gap do not appear unreasonable.

If it is required to estimate the likely frequency of encounter with snowfall at these rates, then each must be associated with a duration. The basic data have a minimum resolvable period of 6 minutes; consideration of the duration of falls exceeding 4 mm/h within clock hours suggests that they may be associated with periods averaging about 30 minutes (over the United Kingdom). In other words, in the course of 500 hours of precipitation at temperatures below 2.5° C, one might expect 10 independent 30-minute falls at the 1 per cent rate, one of which would reach the 0.1 per cent rate.

If overall probabilities are required, it is necessary to know the proportion of time during which precipitation falls on average when the temperature is below 2.5° C—factor A, and the proportion of total time during which the temperature is less than 2.5° C—factor B. These factors in percentage form are given in Table I for the 23 U.K. locations analysed and plotted in Figure 4.

TABLE I—RATES OF PRECIPITATION EXCEEDED FOR 1 PER CENT AND 0.1 PER CENT OF THE TIME DURING WHICH THE SURFACE TEMPERATURE WAS BELOW 2.5°C AND PRECIPITATION WAS FALLING AT 1 mm/h OR MORE; PERCENTAGE OF TIME DURING WHICH THE TEMPERATURE WAS BELOW 2.5°C AND PERCENTAGE OF THAT TIME WITH PRECIPITATION FALLING AT 0.1 mm/h OR MORE (DATA FOR 23 STATIONS IN THE UNITED KINGDOM)

Station	Height above mean sea level (metres)	Period of data (inclusive)	Rate of precipitation (mm/h) exceeded for		Percentages of time	
			1%*	0.1%*	A	B
Aberporth	133	1957-71	4.0	6.0	4.95	6.83
Belfast (Aldergrove)	68	1949-71	4.7	7.0	7.05	11.69
Birmingham (Elmdon)	96	June 1949-71	3.7	5.5	5.55	14.52
Boscombe Down	126	1957-71	3.6	5.4	4.10	13.50
Cardiff (Rhoose)	67	1957-71	3.4	5.1	4.69	10.07
Dishforth	32	1957-Sept. 1965 } Oct. 1965-71 }	3.6	5.3	10.27	14.82
Leeming	32					
Edinburgh (Turnhouse)	33	1957-71	3.8	5.6	4.80	15.00
Eskdalemuir	241	1957-70	4.2	6.1	9.62	23.13
Glasgow (Renfrew)	8	1949-Apr. 1966 } May 1966-71 }	4.2	6.2	5.45	13.08
Glasgow (Abbotsinch)	5					
Kew	5	1957-69	3.2	4.7	4.23	9.29
Kinloss	113	1959-71	4.6	7.0	12.56	14.82
Lerwick	82	1957-70	4.8	7.1	12.22	15.31
London (Heathrow)	25	1949-71	3.5	5.2	3.72	11.42
Manchester (Ringway)	75	1949-71	3.4	5.0	5.17	12.63
Manston	44	1961-71	4.1	6.2	5.80	9.95
Mildenhall	5	1949-Sept. 1969 } 1949-61 }	3.2	5.0	4.07	13.84
Plymouth (Mount Batten)	26					
Prestwick	16	1957-71	4.1	6.1	4.57	12.00
Stornoway	3	1957-71	5.0	7.2	8.15	10.18
Thorney Island	4	Aug. 1958-71	4.0	5.9	3.17	9.66
Tiree	9	1957-71	4.9	7.0	5.20	4.65
Valley	10	1957-71	4.1	6.0	4.24	5.73
Wick	36	1957-71	4.8	7.1	9.64	12.83

* These percentages refer to the period with temperature below 2.5°C and precipitation falling at a rate equalling or exceeding 0.1 mm/h.

A For temperatures below 2.5°C, the percentage of time during which precipitation fell at a rate of 0.1 mm/h or more.

B Percentage of time during which the temperature was below 2.5°C.

It is emphasized that the isopleths drawn in Figure 4 must be regarded as highly smoothed estimates since local factors, especially station altitude, play such a large part. As an example consider Stornoway:

- From Table I—given an air temperature below 2.5°C and snow, we could expect an equivalent rainfall rate of 5.0 mm/h for 1 per cent and 7.2 mm/h for 0.1 per cent of the time.
- Using Factor A and the above—given a temperature below 2.5°C we could expect snow at an equivalent rainfall rate of 5.0 mm/h for less than 0.082 per cent and at 7.2 mm/h for less than 0.0082 per cent of the time. The 'less than' must be included because some occasions will be of rain and some of sleet at ground level.
- Over the year as a whole we should expect snow at the above rates for less than 0.0083 and 0.00083 per cent of the time (factors A and B), or about 1 hour in 10 000 and 1 hour in 100 000 respectively.

From Figures 3 and 4 it is possible to assess probabilities of heavy rates of snowfall for any location in the United Kingdom.

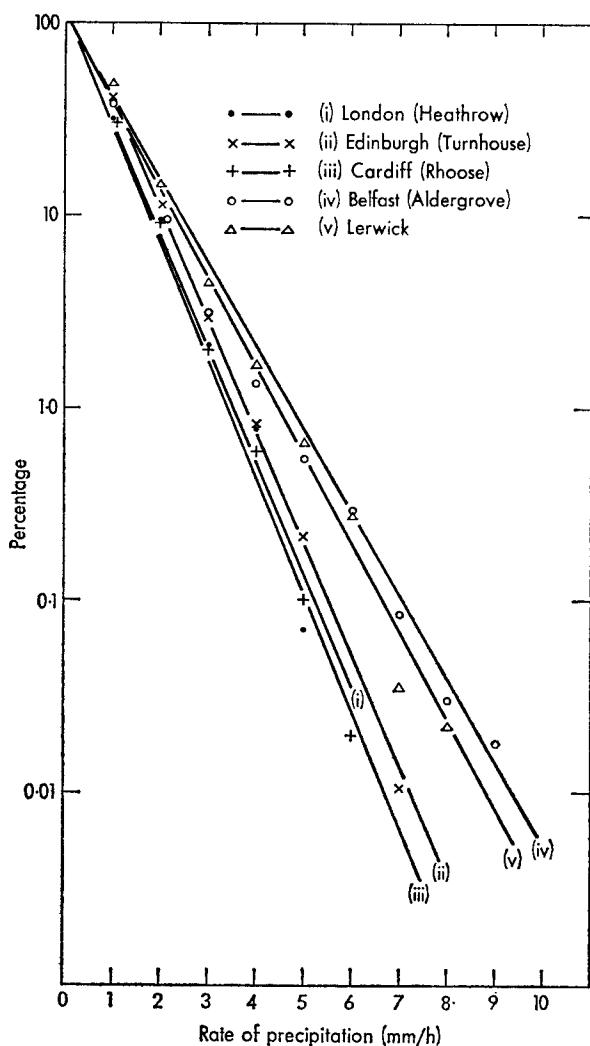


FIGURE 2—PERCENTAGE OF PRECIPITATION EXCEEDING GIVEN RATES AT TEMPERATURES BELOW 2.5°C AT FIVE STATIONS

Discussion. The assumptions, explicit and implicit, in the foregoing analysis have already been mentioned; this section will be concerned with tentatively relating the results to world-wide conditions, and taking into account topography and altitude.

An extension to world-wide conditions. There is no reason to associate heavy rates of snowfall with high latitudes. On the contrary, areas where very cold air occasionally crosses relatively warm stretches of water are subject to the heaviest falls. The United Kingdom is more suitably situated for such falls

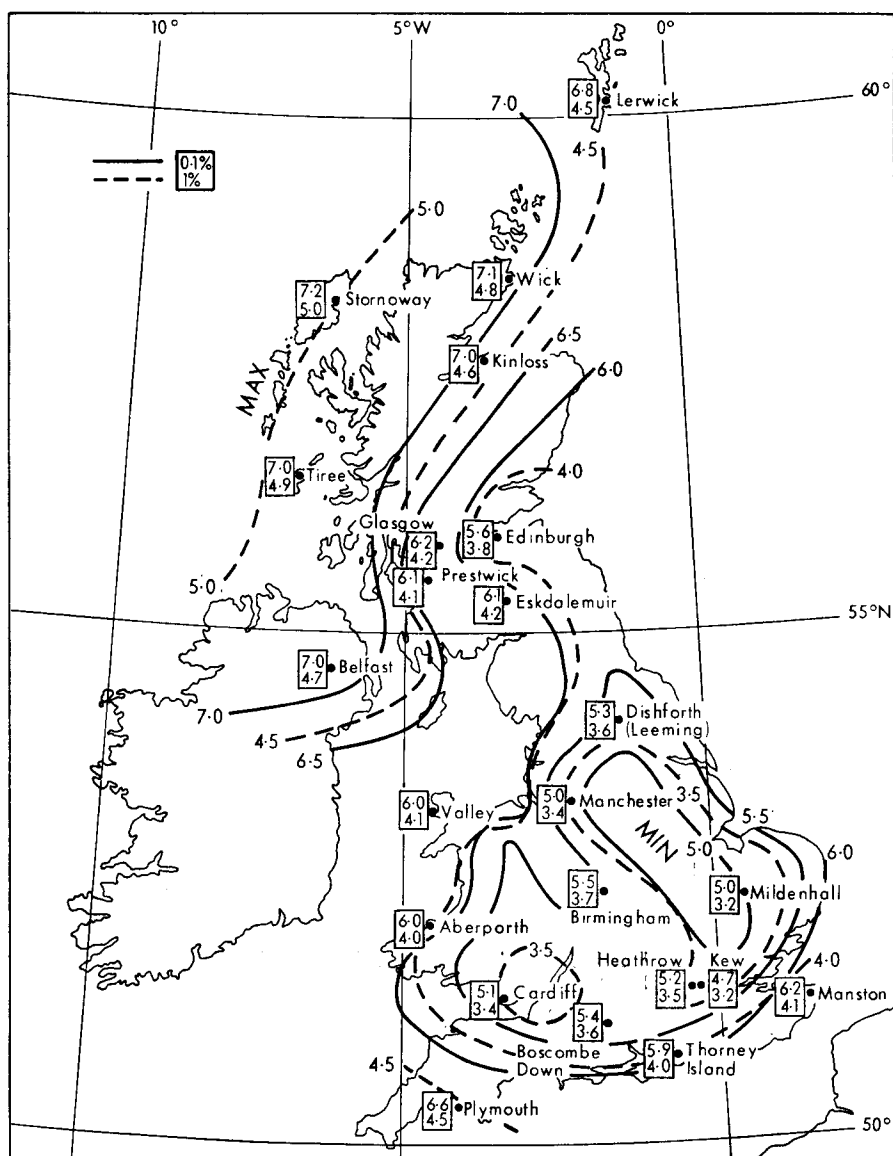


FIGURE 3—RATES OF SNOWFALL EXPRESSED AS WATER EQUIVALENTS IN MILLI-METRES PER HOUR WHICH ARE LIKELY TO BE REACHED FOR 1 % AND 0.1 % OF THE TIME DURING WHICH SNOW FALLS AT A RATE EQUALLING OR EXCEEDING 0.1 mm/h

than most countries, though parts of Japan, the southern Alps, and areas bordering the Great Lakes of North America and the Caspian Sea can be expected to suffer more prolonged heavy snow under favourable circumstances. Not surprisingly data are sparse. The world record snowfall, discussed by Paulhus,⁴ of 76 inches in 24 hours at Silver Lake, Colorado (10 220 ft above mean sea level) averages out at about 7.2 mm/h water equivalent; this suggests

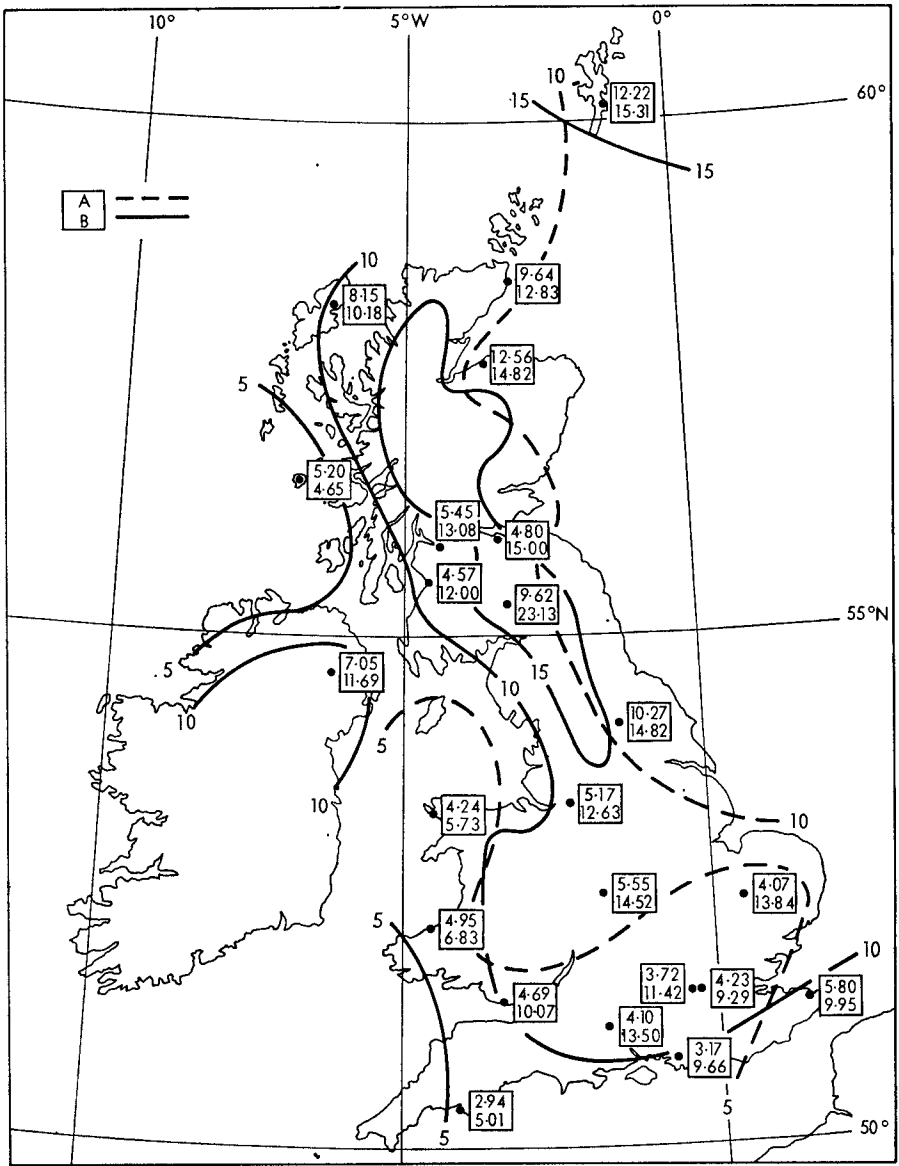


FIGURE 4—PERCENTAGE OF TIME WITH TEMPERATURE BELOW 2.5°C DURING WHICH PRECIPITATION FELL AT 0.1 mm/h OR MORE (A) AND PERCENTAGE OF TIME DURING WHICH TEMPERATURE WAS BELOW 2.5°C (B)

that extreme falls may amount to exceptional durations of heavy snow, rather than exceptionally heavy rates of snowfall. Much has been written about the heavy snowstorms which affect regions bordering the Great Lakes of North America; most aspects are covered in a recent study carried out at the State University of New York.^{5,6} Invariably these storms are associated with large temperature differences between airstream and water of up to 15 degC, and

produce considerable depths of snow of very low density, down to 0.02 g/cm^3 . The probabilities derived here for high snowfall rates over the United Kingdom cannot be expected to apply to the Great Lakes area, but it is considered that, when modified for the appropriate percentage of time with temperatures below 2.5°C , they will provide realistic if slightly exaggerated estimates for most parts.

Topography and altitude. It is necessary to distinguish between these factors: high ground, particularly windward slopes, must be expected to experience a greater proportion of snowfall at high rates, whilst above uniform terrain the rate of precipitation in a non-showery situation would be expected to increase slightly with altitude up to the cloud base (or, in the case of snow, up to that level below the cloud base at which the air is saturated with respect to ice) and to decrease above this level.

A crude assessment of the probability of heavy snow at different altitudes can be made by assuming a mean temperature lapse rate of 2°C per 1000 ft* and using a modified B factor. For example, we may regard a surface temperature of less than 2.5°C as corresponding to snow in the lowest 1250 ft, 2.5 to 5.0°C to the 1250–2500-ft altitude band and so on. The mean annual percentage time during which the surface temperature lies below the chosen threshold can then be used instead of the tabulated B factor; Figure 5 gives curves for four locations which represent most areas of the United Kingdom. The amount by which the proportion of precipitation at high rates increases with surface temperature is to some extent compensated by the loss of that part which forms below the altitude of interest; nevertheless, probabilities calculated in this way should only be regarded as order-of-magnitude assessments. If interest is strictly confined to the surface then probabilities can be reduced by the proportion of precipitation falling as rain or sleet at temperatures below 2.5°C . An analysis by Murray⁷ suggests that this is about 60 per cent, whilst more recently Auer⁸ reported it to be 50 per cent in the United States.

The problem of correcting for mountainous terrain is rather different. Perhaps the best simple adjustment where possible is to scale the percentages of precipitation at high rates at the nearest low-level station for which data are available by the ratio of the annual average rainfall in the area of interest to that at the low-level station.

Conclusion. The data presented enable rough estimates to be made of the probability of occurrence of snowfall exceeding a selected threshold rate in a given area. The procedure is as follows:

- (a) Select a suitable station (or region) from Table I or Figure 3.
- (b) Use 1.0 and 0.1 percentage values to draw a straight-line curve on semi-logarithmic paper as in Figure 2.
- (c) Read off the percentage against the required rate.
- (d) Modify as required, using the factors in Figure 4 and an altitude correction if necessary. In particular, reduce by 60 per cent if interest is strictly confined to ground level.

* This corresponds approximately to the saturated adiabatic lapse rate for near 0°C between 1000 and 800 mb.

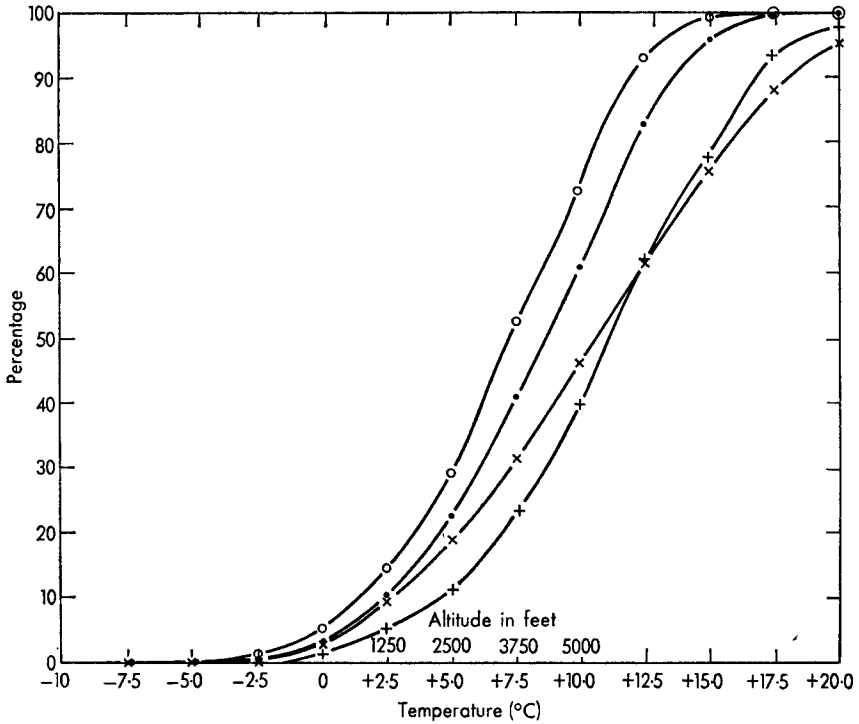


FIGURE 5—PERCENTAGE OF TIME DURING WHICH THE SURFACE TEMPERATURE IS BELOW GIVEN VALUES AT FOUR STATIONS

x — x Kew
 ● — ● Stornoway
 ○ — ○ Lerwick
 + — + Plymouth

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**WORLD METEOROLOGICAL ORGANIZATION COMMISSION
FOR AGRICULTURAL METEOROLOGY (CAgM) SIXTH
SESSION—WASHINGTON, OCTOBER 1974**

By C. V. SMITH

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The Sixth Session of the WMO Commission for Agricultural Meteorology was held in the International Conference Room of the U.S. State Department in Washington, D.C., from 14 to 25 October 1974. The session was opened by the Hon. Earl L. Butz, U.S. Secretary of Agriculture, and Mr Taha, President of WMO and Dr Davies, Secretary-General of WMO, spoke to the conference on the 21st. Representatives of 55 countries and of non-governmental international organizations, including the United Nations Food and Agriculture Organization, took part in the plenary conference; the United Kingdom delegates were Messrs R. Murray and C. V. Smith.

It might be supposed that, in a turbulent world, the march of the seasons and the patterns of agriculture would at least provide evidence of a changeless scene, and that one meeting of the Commission would be much like its predecessors. Not so. In only three years, the concern in some countries over food surpluses has been transformed by a general concern over the low level of world food reserves and the threat and appearances of food shortages. The general awareness, even among lay people, of the possibility of climatic change, and of the profound consequences of season-to-season weather variations in the marginally productive lands of parts of Africa and Asia, has led to studies of the role of the weather in the seasonal variability of crop yields in some of the main grain-producing areas of the world. The residual variance due to weather takes on greater importance as the upward trend in yields, arising from advances in technology over the past 30 years, begins to flatten out, whilst population projections continue upwards. All these developments, which have taken place during the past few years, have dictated the changes in the role and direction of effort of the Commission for Agricultural Meteorology.

In its early days, the Commission acted as a forum for the exchange of information and techniques, and for authoritative reviews of the present position of agrometeorological activities. This important work obviously still goes ahead, but the appearance of operational Working Groups is a new and far-reaching departure from the past. The new or reconstituted groups, for example, on International Experiments for the Acquisition of Crop Weather Data (wheat and lucerne), deliberately set out to generate new information; from closely monitored field experiments, the phenological, field and weather data necessary to derive quantitative relationships (models) of crop growth and yield are being actively sought. Further emphasis on this operational aspect of the Commission's work was given by the establishment of a Working Group on Weather and Climate as related to World Food Production, charged, among other things, with a study of the expanded procedures necessary to the World Weather Watch data-collection system, which would provide real-time data to enable up-to-date areal assessments of crop performance, and, it was to be hoped, some forewarning of where, and by how much, surpluses and deficiencies in yields would arise. Further groundwork for this effort was laid by the

appointment of a Rapporteur on Mathematical Simulation Modelling in Agrometeorology and the decision to hold a symposium on techniques in crop-weather analysis.

The Working Group on Weather and Animal Diseases was re-established and is again composed of people who place their emphasis on action rather than on review, and who see their purpose as that of initiating and developing warning and forecasting systems for those weather-sensitive diseases about which something is known already, and to undertake more speculative studies on the role of weather in some parasitic diseases and in mycotoxicoses. The impact of weather and environment on intensive livestock production had been well covered by U.K. contributions in the past. Further requirements (until the next session) might, it was decided, be adequately met by a symposium on animal husbandry, which would now take into consideration the management of extensive grasslands and those resources that can only be adequately exploited by use of livestock.

The view of the Commission on the need for action and application, rather than for words, was elaborated in the Recommendation to Member Countries to develop extended forecasts for agriculture. The terms of reference of the Rapporteur appointed on this topic direct attention to many areas such as water usage and requirements, field-work days of all kinds, and warnings on pests and diseases, etc. for which the basis for advice already exists in this country. These involve some elaborate manipulation of weather parameters and, though a great many U.K. farmers possess the technical competence to carry it out, the necessary data cannot be derived from general weather forecasts. The implications of current weather and weather forecasts, for agriculture, could and should be examined more than they are at present. Certainly many countries take the view that such help should be provided, and Dr Landsberg, President of the Commission for Special Applications of Meteorology and Climatology (CoSAMC), in his cogent arguments for such a service, was in no doubt of the need for, the farmer's response to, and the financial return from, such a service.

It is indeed necessary to emphasize the practical economic value of agrometeorological services; so long as there are limited financial resources, there is the need for concrete examples to highlight the benefit/cost ratio of agrometeorological services. Again a Rapporteur was appointed for this purpose.

Any meeting of the Commission (generally at intervals of four years) has three main tasks:

- (a) to review progress and technical work since the previous meeting;
- (b) to identify and analyse global agricultural problems related to weather and climate; and
- (c) to propose a further programme of research, training and operational services.

Work under (a) above at Washington was rather restricted by the absence of many completed reports; these were mostly available to the Secretariat but, in marked contrast to previous sessions, were not all distributed before the meeting. The availability of single copies for inspection in the conference chamber did little to relieve an air of unreality in some of the discussions until they moved on to the items listed in (b) and (c) above. This is perhaps the point at which to mention that the report by J. W. Davies (Meteorological Office) on the Meteorological Effects of Soil Cover has been approved for

publication as a WMO *Technical Note*. Other U.K. contributions found their place in reports on Weather and Animal Disease and in collected papers on soil erosion.

The analysis of problems and of key areas for future work can be subdivided into the following broad fields: methodology; meteorological factors affecting soils and crops, and plant injury, pests and disease; meteorological factors affecting animal production, and animal pests and disease; economics; and training. The subject matters that hold a challenge for the United Kingdom have already been outlined in the early part of this article, but among the topics for the many Working Groups and Rapporteurs appointed at CAgM-VI, we find many where U.K. expertise would, of necessity, be limited to problem solving as distinct from field experience. These include work on rice, the epidemiology of the cassava mite, forestry, water use and land-use management under severe climatic conditions, etc. Essentially the demand for such work represents a call for help by the developing countries; commonly this call for help has taken the form of requests for expanded observational networks and manpower training, a procedure which obscures the underlying necessity for aid in achieving some basic understanding of agrometeorological problems, for aid in identifying key areas for work, and for aid in translating understanding into application and operating systems. The problems for both developing and more advanced countries are thus seen to be closely related and often complementary. The small number of agrometeorologists in the United Kingdom, for example, is not enough to support a training programme; the more difficult problems are not necessarily technical but are related to organizational renewal, development and change.

There is little doubt that the discussions at the 6th Session of CAgM were always harmonious and often fruitful although sometimes rather lengthy. However, the success of any meeting is not easily assessed. Many delegates must surely have returned to their own countries having gained something of personal value from friendly contact with colleagues from widely scattered parts of the world. However, the more tangible success of the meeting in Washington will probably be measured by the quality of the technical reports expected to emerge in the next four years from the nine Working Groups and 14 Rapporteurs appointed by the Commission.

REVIEW

Atmospheric waves, by T. Beer. 255 mm × 195 mm, pp. xvi + 300, *illus.*, Adam Hilger Ltd, 29 King Street, London WC2 E8JH, 1974. Price: £16.

There is no doubt that the subject of atmospheric waves is complex and much of the literature is difficult for the more casual reader to comprehend. For this reason a book carefully presenting the essential characteristics of the different classes of waves which occur in the atmosphere would have been most welcome. The author states that he has intended this book for both novices and experts in atmospheric physics and other workers in earth sciences. However, the book not only fails to meet the requirements of either group but owing to its muddled, incomplete, and occasionally erroneous treatment of the subject, it cannot be recommended. In such a complex subject the failure to meet the requirement of both groups might be regarded as inevitable, but the very poor standard of the material is made especially disappointing by the useful references to excellent review books and papers.

The book has chapters inaccurately entitled 'The theory of atmospheric waves; Waves in real atmospheres; Waves in the lower atmosphere; Atmospheric tides; Waves in the ionosphere; Non-linear effects'. The material covered not only includes the sound, internal gravity, Rossby, and other types of waves expected but also digressions on subjects such as computational stability and turbulence. The author's own field of work concerns waves in the upper atmosphere and it is this part of the material which is dealt with in the most detail. Whilst the treatment of this area is reasonably accurate, its value is lost in its muddled presentation and links with the thoroughly inadequate treatment of waves in the lower atmosphere.

Inaccuracies vary between mathematical ones, such as an erroneous definition of dispersion, and a statement that the Coriolis and centrifugal forces may be incorporated into the geopotential altitude, and interpretative ones which are contradicted by the references given to support them. The assertion that atmospheric long waves are Rossby waves and 'free' when they arise 'from baroclinic, barotropic, and thermal forcing' or 'forced' when 'due to mountains and continents' whilst cyclone waves are due to barotropic instability of meridional shear is certain to confuse readers. The section on turbulence is especially grim and concludes with the suitably erroneous statement that the low-wave-number planetary waves produced by mountains and continents have a k^{-3} spectral distribution. The mathematically dubious treatment of baroclinic instability is the case with zero static stability (in spite of references to Eady and other work which crucially contains a static stability) and naturally produces only a long-wave cut-off. The short-wave cut-off, which a static stability is crucial in creating, is attributed to the 'effect of vertical motions on the meridional temperature gradient'. We are told that when the Rossby number of a mountain is less than about 0.5 the column of air above it is stagnant in a 'Taylor column'. There is no such Rossby-number criterion for the occurrence of a Taylor column and his statement leads to the erroneous conclusion that such 'Taylor columns' occur frequently in the atmosphere. The book contains many other serious errors, and it is surprising that the publishers awarded this disappointing and expensive book the 'Adam Hilger Prize'.

P. J. MASON

LETTER TO THE EDITOR

An objective aid for estimating the night minimum temperature of a concrete road surface

A minor error has been noticed in the above-named paper (THORNES, J. E.; *Met Mag*, London, 101, 1972, pp. 13-25). On page 18, section (c), it is stated that Swinbank's formula for estimating outgoing radiation, E , is

$$E = 5.31 \times 10^{-14} T^6 \text{ mW/cm}^2.$$

In fact this is Swinbank's formula for incoming long-wave radiation from clear skies, R , and

$$\begin{aligned} E &= \sigma T^4 - R \text{ mW/cm}^2 \\ &= (\sigma T^4 - R) \times 1.4335 \times 10^{-2} \text{ cal/(cm}^2 \text{ min)}, \end{aligned}$$

where σ = Stefan's constant, for which Swinbank used the value

$$5.77 \times 10^{-9} \text{ mW/cm}^2 \text{ K}^{-4}.$$

The point only occurs in an outline of a possibility, which was not pursued, of removing a variable from the argument. It does not affect the basic method presented in the paper.

*Meteorological Office,
Bracknell.*

C. L. HAWSON

AWARDS

ROYAL METEOROLOGICAL SOCIETY AWARD TO THE DIRECTOR-GENERAL

The Royal Meteorological Society has awarded its Symons Memorial Gold Medal to the Director-General of the Meteorological Office, Dr B. J. Mason, C.B., F.R.S. The citation reads as follows:

The Symons Memorial Gold Medal for 1975 is awarded to Dr B. J. Mason for his outstanding contributions to the development of the science of meteorology, and, in particular, for his contributions to the understanding of the physics of clouds. Not only has Dr Mason carried out numerous fundamental studies of cloud microphysics and electrification, and produced in his 'Physics of clouds' the definitive work on the subject, but he has, as Professor of Cloud Physics at Imperial College from 1961 to 1965 and subsequently, exerted a major and much needed influence on the study of cloud physics which has assured its development on a sound scientific basis.

As Director-General of the Meteorological Office since 1965, he has, by his outstanding scientific leadership and encouragement, fostered major developments over a very wide range of meteorology both in the United Kingdom and abroad. These include development of numerical weather prediction and computer study of climate and climatic changes as well as such international experiments as the Atlantic Tropical Experiment (GATE) of the Global Atmospheric Research Programme for which he undertook onerous responsibilities as chairman of the Tropical Experiment Board. The sound but rapid developments of stratospheric physics both nationally and internationally in an age of new technologies owe much to his efforts.

AWARD OF IMO PRIZE TO DR JOSEPH SMAGORINSKY

We note with pleasure that the nineteenth International Meteorological Organization Prize for outstanding work in meteorology and in international collaboration has been awarded to Dr Joseph Smagorinsky, Director of the Geophysical Fluid Dynamics Laboratory of the United States National Oceanic and Atmospheric Administration.

CORRECTIONS

Meteorological Magazine, January 1975, p. 23, caption to Figure 5, last line: for 'From Figures 2 and 4' read 'From Figures 3 and 4'.

Meteorological Magazine, March 1975, p. 83, Table VI. In the column headed *S*, the entry opposite 'September' should be '0.44 *G* + 0.20'. On page 84, Figure 1, the *y*-axis for the October graph should be numbered from 0 to 4 and not from -1 to 4.

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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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SHIPBOARD PRESSURE MEASUREMENTS DURING JASIN 1972

By N. THOMPSON

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Summary. Shipboard pressure data obtained during the Joint Air-Sea Interaction Experiment (JASIN) in 1972 have been analysed in some detail. The results suggest that typical instrumental error for the Meteorological Office Precision Aneroid Barometer (PAB) is about 0.2 mb. Random errors due to ship-induced accelerations were about 0.1 mb. Sets of observations obtained for different ship headings relative to wind demonstrated variations of measured pressure with heading of several tenths of a millibar in winds of force 4 or 5 in spite of the barometers' being connected to well-exposed static heads. Intercomparisons of pressure readings obtained when ships were adjacent showed inconsistencies due either to short-term barometer drift or, more probably, to reading errors which varied between observers.

Introduction. The Joint Air-Sea Interaction Experiment (JASIN) is a meteorological and oceanographic investigation of mixing processes in the lower troposphere and upper ocean on time scales of up to a few weeks and horizontal scales of up to about 100 km. Preliminary experiments in the series took place in 1970 and 1972 near ocean weather station (OWS) 'J' (52½°N, 20°W), and the main experiment is planned for the summer of 1978 near OWS 'I' (59°N, 19°W). At least three ships are required for the meteorological programme, spaced far enough apart to allow the calculation of divergence with reasonable accuracy from their upper-wind measurements, but also sufficiently close to support the oceanographic programme effectively and to ensure that atmospheric mesoscale systems cross the array in a time short enough for their identity to be preserved—say a few hours. These requirements conflict to some extent and if only three ships are available then a compromise is necessary, with a ship-spacing of about 100 km.

The meteorological programme is concerned *inter alia* with the relationships between surface fluxes and large-scale parameters. One of the latter is the surface geostrophic wind

$$V_g = \frac{1}{\rho f} \nabla p \times \kappa,$$

where ρ is the air density, f the Coriolis parameter and κ the unit vertical vector. There have always been doubts whether the size of the area enclosed by the JASIN ships would be large enough to allow the measurement of the

pressure gradient with sufficient accuracy to provide useful estimates for V_g , and in both the 1970 and 1972 exercises there were special experiments to investigate this point. An error in pressure measurements of 0.1 mb over a distance of 100 km would produce a wind-speed error of 0.8 m/s, or for a typical geostrophic speed of 10 m/s a direction error of 5° . It is believed that errors even as small as these are barely acceptable for JASIN.

In 1970 the pressure experiment was carried out with sensors mounted on meteorological buoys: the results¹ demonstrated the inadequacy of the sensors for measurements of the required very high accuracy. The 1972 experiment made use of buoys with different pressure-measuring systems supplied and maintained by the University of Miami, and also investigated the possibility of obtaining satisfactory data from instruments on board ship. The present note discusses these ship observations.

The difficulties of making atmospheric-pressure measurements of very high accuracy are greater when the observations are made aboard ships rather than on land. The main errors likely to arise are briefly as follows:

(a) Changes may occur in the sensor calibration and these are detectable usually only on recalibration: since recalibration is not feasible on board ship the nature of the shift (for instance sudden change or slow drift) is not known and there is uncertainty about which calibration figure to use.

(b) Ship's motions (heave, pitch and roll) produce fluctuations in pressure caused by changes in height of the sensors and by the acceleration forces on the transducer and its mounting. The first type of fluctuation can be reduced to negligible amounts either by inserting a suitable constriction in the pipe connecting static head and sensor or alternatively by averaging over several cycles of the ship's motion. Acceleration forces can also be averaged out provided that the mean orientation of the sensor was that in which it was calibrated, but if the instrument is tilted, for example by incorrect levelling when mounted or by the ship's listing in a strong beam wind, then errors may result.

(c) With sensors such as the Meteorological Office Precision Aneroid Barometer (PAB) where manual setting is required, leading to some imprecision, different observers may arrive at a different setting for the same ambient pressure, especially when the ship's motion is vigorous.

(d) The ship will disturb the airflow from its free-stream pattern and then in spite of the use of static heads the measured pressure will differ from that in undisturbed flow. If it is assumed that Bernoulli's equation holds for this case then departures of ± 5 m/s from a free-stream velocity of 10 m/s produce pressure changes of -0.75 and $+0.45$ mb: even changes in velocity of ± 1 m/s cause significant variations ($\approx \pm 0.1$ mb) at this mean speed.

(e) In a rolling ship with the static head above the pressure sensor there will be a net upward force on the air in the pipe connecting them (Pollard, personal communication, 1971). The mean error is about -0.02 mb for a roll angle of ± 10 degrees with a period of 6 seconds and with the static head 15 metres above the barometer.

Experimental design and instrumentation. The three ships involved in JASIN 72 were O.W.S. *Weather Adviser* (on Station 'J'), R.R.S. *Discovery* and m.v. *Researcher*, spaced 100 kilometres apart at the corners of an equilateral triangle. The pressure sensor used on all ships was the Meteorological Office Precision Aneroid Barometer (PAB).^{2,3} This incorporates a capsule stack whose

deflexion is measured by a micrometer calibrated in millibars and tenths: contact between micrometer and capsule is indicated by an electrical make-and-break circuit. The display can be read with a precision exceeding 0.05 mb but there is a dead zone in the micrometer system of about 0.05 mb and a reading resolution better than this is not justified. The instruments were calibrated before and after the experiment in the Meteorological Office test room against a precision Bourdon gauge, readings being given to 0.1 mb. Three PABs were used on each ship—it was hoped that the multiple pressure observation would allow an improvement in the accuracy of the mean of the measurements on each ship as well as providing data for assessing the performance of the aneroids by intercomparison of the readings. On all ships the PABs were connected to a standard Meteorological Office static head mounted in a reasonably well-exposed position; these positions and those of the PABs appear in Table I.

TABLE I—BAROMETERS AND STATIC HEADS

Ship	Barometer type, position and approximate mean height above mean sea level	Static head type, position and mean height above sea level
<i>Weather Adviser</i>	3 PABs, Meteorological Office, 3 m.	<ol style="list-style-type: none"> 1. Meteorological Office pattern, port side of platform on mainmast, 18 m. 2. Meteorological Office pattern, starboard side of platform on mainmast, 18 m. 3. Meteorological Office pattern, on mast above shelter, 15 m.
<i>Researcher</i>	3 PABs, Laboratory, 3 m.	Meteorological Office pattern, starboard side of mast above wheelhouse, 9 m.
<i>Discovery</i>	<p>3 PABs, gravity room, 3 m.</p> <p>1 PAB, bridge, 12 m. Kollsman, either (a) bridge, 11 m, or (b) gravity room, 2 m.</p>	<ol style="list-style-type: none"> 1. Meteorological Office pattern, starboard side of platform on mainmast, 18 m. 2. Meteorological Office pattern, port side of lookout area of monkey island, 13 m. 3. Miami (Snyder) pattern, starboard side of monkey island, 13 m.

The pressure distribution over any object obstructing the airflow differs from that in the free stream (page 158) so that apart from any errors introduced by the transducers the pressure observations from ships will always be in error except in very light winds. To obtain some information on these errors additional static heads were mounted on *Weather Adviser* and *Discovery* (Table I). On *Adviser* an extra head was mounted on the mainmast, at the same level as, but on the opposite side to, the existing head, and another was placed on a mast about 4 m above the top of the balloon shelter (aft of the mainmast). Valves were used to connect the selected head to the PABs. On *Discovery* the extra head was placed on the bridge. *Discovery* also carried two additional barometers, a PAB mounted above the bridge deck and connected to the Meteorological Office head on the bridge, and a Kollsman sensor mounted either in the gravity room or on the bridge deck, and capable of connection to either of the two Meteorological Office heads or to a University of Miami head on the bridge.

The fluctuations produced by the change in height of the PABs above sea level due to ship's motion were reduced to less than ± 0.1 mb by fitting 'damping caps' (constrictions) to the inlet pipes of the barometers.

The observations. The main series of measurements were made at 1-hourly intervals on all ships. The PABs were read twice in the sequence 1-2-3, 1-2-3, using the mainmast static head on *Adviser* and the foremast head on *Discovery*. There were additional measurements made on each ship (Table II) the principal object of which was the determination of the effect on the observed pressure of changes in relative wind direction. *Researcher* carried out two series of this type in winds of force 3 and 5, the PABs being read in the same sequence as for routine observations. *Adviser* also carried out two series in similar winds, but here observations were made with all three static heads at each heading, each thus producing 18 pressure readings. Two similar series were carried out aboard *Discovery*, with 12 readings of each PAB at the various headings. Five intercomparisons of PABs on different ships were made, in all but one case with only two adjacent ships (Table II).

TABLE II—SPECIAL PRESSURE OBSERVATIONS DURING SEPTEMBER 1972

Series number	Ship	Period Date/Time (GMT)	Barometer and static heads	Notes
1	<i>Researcher</i>	06/1022-06/1110	3 PABs, mast head	Measuring pressure at 16 different headings relative to wind; each PAB read twice on each heading.
2	<i>Researcher</i>	10/1055-10/2055	3 PABs, mast head	Various different relative headings: PABs read twice on each heading.
3	<i>Adviser</i>	10/1410-10/1535	3 PABS, all static heads	16 different relative headings: PABs read twice for each static head on each heading.
4	<i>Adviser</i>	20/0800-20/0848	3 PABs, all static heads	16 different relative headings: PABs read twice for each static head on each heading.
5	<i>Discovery</i>	09/0000-23/0700	Kollsman (bridge), Miami head	100-second averages every 5 minutes.
6	<i>Discovery</i>	23/1150-23/1950	Kollsman (gravity room), mast head	100-second averages every 5 minutes.
7	<i>Discovery</i>	23/2005-24/0315	Kollsman (gravity room), mast head	100-second averages every 5 minutes.
8	<i>Discovery</i>	24/0320-24/0548	Kollsman (gravity room), 3 PABs, mast head	16 different relative headings: PABs read 12 times for each heading. 120 Kollsman 1-second averages at 1.5-second intervals on each heading; also single 100-second averages before ship changed heading.
9	<i>Discovery</i>	24/0550-25/1515	Kollsman (gravity room), mast head	100-second averages every 5 minutes.
10	<i>Discovery</i>	25/1520-26/1615	Kollsman (bridge), Miami head	100-second averages every 5 minutes.
11	<i>Discovery</i>	26/1620-26/2305	Kollsman (bridge), bridge Met. Office head	100-second averages every 5 minutes.

TABLE II—continued

Series number	Ship	Period Date/Time (GMT)	Barometer and static heads	Notes
12	<i>Discovery</i>	26/2318– 27/0132	3 PABs, mast head, bridge PAB, bridge Met. Office head, Kollsman (bridge), all three static heads	8 different relative headings: gravity room PABs read 12 times for each heading, followed by 18 readings of bridge PAB. 100-second averages from Kollsman using mast head and bridge, Met. Office head (both simultaneous with PAB readings), and Miami head on each heading.
13	<i>Discovery</i>	27/0140– 28/0850	Kollsman (bridge), Met. Office bridge and mast head	100-second average every 5 minutes.
14	<i>Discovery</i>	28/0855– 28/1340	Kollsman (bridge), alternate heads (Met. Office and Miami)	100-second average every 5 minutes.
15	<i>Discovery</i>	28/1340– 29/1150	Kollsman (bridge) Miami head	100-second-averages every 5 minutes.
16	<i>Discovery</i> <i>Adviser</i>	04/1410– 04/1420	3 PABs, mast head 3 PABs, all heads	Intercomparison. Each PAB read twice on <i>Discovery</i> , 3 times for each head on <i>Adviser</i> .
17	<i>Discovery</i> <i>Researcher</i>	05/1910– 05/1940 05/1855– 05/1955	3 PABs, mast head 3 PABs, mast head	Intercomparison. Each PAB read twice at 15-minute intervals on both ships.
18	<i>Discovery</i> <i>Researcher</i>	13/1010– 13/1155 13/0955– 13/1255	3 PABs, mast head 3 PABs, mast head	Intercomparison in very light winds. PABs read twice at 15-minute intervals.
19	<i>Adviser</i> <i>Discovery</i> <i>Researcher</i>	18/0800– 18/0900 18/0740– 18/0855 18/0755– 18/0855	3 PABs, port mast head 3 PABs, mast head 3 PABs, mast head	Intercomparison. PABs read twice at hourly intervals on <i>Adviser</i> . Read twice at 15-minute intervals on <i>Discovery</i> and <i>Researcher</i> .
20	<i>Adviser</i> <i>Discovery</i>	27/1810– 27/2010 27/1825– 27/2010	3 PABs, all heads 3 PABs (gravity room), mast head. Bridge PAB, bridge head.	Intercomparison. PABs read twice for each head on <i>Adviser</i> at 15-minute intervals. Gravity room PABs read twice at 15-minute intervals, bridge PAB single reading every 15 minutes on <i>Discovery</i> .

On board *Discovery* the Kollsman sensor was used in association with different static heads to obtain extensive data, occasionally simultaneously with PAB observations and sometimes sharing static heads with them. Details of these trials are also given in Table II.

Results and discussion

(a) PAB readings.

(i) *General results.* Before detailed discussion of the results it is appropriate to consider the magnitude of two of the pressure errors described in the Introduction. One important cause of uncertainty is the change of calibration revealed after recalibration of the sensors (page 158). The PAB corrections found before and after JASIN 72 are shown in Table III. Changes were very small for all three PABs on *Discovery* (0.1 mb or less) and usually less than 0.2 mb for *Adviser* but (presumably coincidentally) only one of *Researcher's* instruments showed a drift of less than 0.2 mb. Because of lack of information on the causes of the changes it had to be assumed that they were due to linear drifts with time.

TABLE III—BAROMETER CORRECTIONS

Ship	PAB	980 mb	Correction to be added		1050 mb	Calibration date
			1000 mb	1020 mb		
			millibars			
Adviser	1	+0.1	0.0	+0.1	+0.1	15 June 1972
		+0.2	+0.2	+0.1	+0.3	19 October 1972
	2	+0.1	0.0	0.0	+0.1	2 August 1972
		0.0	+0.1	+0.1	+0.1	19 October 1972
	3	-0.1	-0.1	-0.1	-0.1	2 August 1972
		0.0	0.0	0.0	+0.1	19 October 1972
Researcher	1	+0.1	+0.1	+0.1	+0.2	15 June 1972
		+0.3	+0.3	+0.3	+0.5	19 October 1972
	2	0.0	-0.1	-0.1	+0.1	2 August 1972
		+0.3	+0.3	+0.3	+0.4	19 October 1972
	3	0.0	0.0	0.0	+0.1	2 August 1972
		0.0	-0.1	+0.1	+0.3	19 October 1972
Discovery	1	-0.1	0.0	0.0	+0.1	15 June 1972
		0.0	+0.1	+0.1	+0.2	19 October 1972
	2	-0.1	-0.1	-0.1	-0.1	7 August 1972
		-0.1	-0.1	-0.1	-0.1	19 October 1972
	3	0.0	0.0	0.0	+0.1	7 August 1972
		+0.1	0.0	+0.1	+0.2	19 October 1972

Errors are also introduced by the difficulties of averaging out the effects of ship-induced acceleration (page 158). They can be reduced by mounting the PABs on fore-and-aft bulkheads because the sensitivity to rotation about an axis (A) along this direction is substantially less than for rotation about a horizontal axis at right angles to this (B). This is demonstrated by Table IV where typical changes in pressure readings for rotation about both axes are given. Because of the difficulty of finding suitable mounting points for the PABs on the ships it was only possible to use fore-and-aft bulkheads on *Researcher*; the other aneroids were mounted athwartships. Observers were instructed to average out as far as possible the fluctuations due to ship's motion (heave, pitch and roll) though this was difficult to do in the heavier seas. Systematic errors to be expected from the barometer's sensitivity to tilt would occur as a result of the ship's taking up a mean angle of roll due to wind on either beam (page 158). For *Adviser* and *Discovery* the magnitude of the error would be about 0.025 mb per degree of

roll, with the sign of the error positive or negative for roll towards port or star-board respectively. The error for *Researcher* was about 0.005 mb per degree of roll.

TABLE IV—SENSITIVITY OF PRECISION ANEROID BAROMETERS TO PITCH AND ROLL
(OBTAINED FROM STATIC TILT TESTS)

Angle of pitch (about axis B) degrees	Angle of roll (about axis A) degrees	Change in reading millibars
0	0	—
+10	0	0.2
+20	0	0.5
+30	0	0.75
-10	0	-0.3
-20	0	-0.55
-30	0	-0.75
0	+10	0.05
0	+20	0.1
0	+30	0.2
0	-10	-0.05
0	-20	-0.1
0	-30	-0.15

All pressure data recorded during JASIN 72 were 'as read' and corrections for calibration changes and for height above sea level were applied when the data were processed on an ICL 1905 computer. Allowances were made where necessary for variations in ship's draught during the voyage (changes of calibration with temperature were ignored: typical changes are about 0.1 mb for a 10-degC variation of temperature).

The resulting 10 000 or so routine pressure values are summarized in Table V in the form of mean daily pressure for each PAB. It is clear that there are persistent systematic differences between corrected data from different aneroids. Disagreements as large as 0.3 mb occurred between the readings of barometers which showed the largest calibration changes with time (for example the PABs on *Researcher*) and in these circumstances an accuracy in measurement of the pressure at the static head of ± 0.1 mb clearly cannot be claimed even when an average is taken of the readings from three PABs. On the other hand changes in differences between PABs are usually small, and, with the exception of one sensor on *Researcher*, within the range ± 0.1 mb.

The corrected PAB readings (x_{ijk} , $i=1,2$; $j=1, \dots, 3$; $k=1, \dots, 24$ (i =reading number, j =barometer number, k =hour number)) showed considerably more scatter than their daily means

$$\frac{1}{48} \sum_{i,k} x_{ijk}.$$

If it is assumed that differences between these daily means also apply to the hourly values it is then possible to correct the six observations obtained each hour on each ship to a common reference to give a new set of values x'_{ik} ($i=1, \dots, 6$). The daily averages of the resulting standard deviations

$$\frac{1}{24} \sum_k \left[\frac{1}{6} \sum_i (x'_{ik} - \frac{1}{6} \sum_i x'_{ik})^2 \right]^{\frac{1}{2}}$$

are given in Table VI. The least scatter was always shown by the readings on *Discovery*, a compliment to the observers, but probably the result also of the greater stability of this ship.

TABLE V—DAILY MEAN PRESSURES (LESS 1000 mb) AS MEASURED ABOARD THREE SHIPS IN SEPTEMBER 1972

PAB Date	Admirer (A)			Discovery (D)			Researcher (R)			Means			State of sea *
	1	2	3	1	2	3	1	2	3	A	D	R	
2				34.60	34.60	34.74	34.59	34.71	34.68		34.65	34.66	M→S
3				36.88	36.88	37.03	36.90	37.08	36.99		36.93	36.99	S
4	32.70	32.86	32.89	32.78	32.85	32.99	33.37	33.52	33.55	32.81	32.87	33.48	M
5	24.93	25.12	25.12	25.07	25.13	25.24	25.25	25.43	25.53	25.06	25.15	25.40	M
6	16.30	16.46	16.46	16.01	16.08	16.16	16.14	16.24	16.27	16.41	16.08	16.22	S to M
7	14.79	15.02	15.05	15.16	15.24	15.32	15.31	15.50	15.46	14.95	15.24	15.42	M
8	16.07	16.24	16.27	16.96	17.02	17.10	16.96	17.17	17.17	16.19	17.03	17.10	M→R
9	19.29	19.53	19.50	19.29	19.32	19.43	20.04	20.31	20.35	19.44	19.35	20.23	R→M
10	24.10	24.28	24.31	23.86	23.85	23.95	24.37	24.61	24.68	24.23	23.89	24.55	M
11	27.30	27.46	27.50	27.29	27.31	27.39	27.56	27.83	27.90	27.42	27.33	27.76	M
12	29.27	29.47	29.53	29.27	29.29	29.41	29.25	29.51	29.57	29.42	29.33	29.44	M
13	29.34	29.50	29.57	29.47	29.50	29.62	29.36	29.57	29.65	29.47	29.53	29.53	M
14	27.42	27.56	27.61	27.73	27.76	27.86	27.12	27.37	27.43	27.53	27.78	27.31	M
15	25.78	25.95	25.99	25.85	25.87	25.94	23.98	24.23	24.34	25.91	25.89	24.18	S
16	26.49	26.68	26.73	26.24	26.27	26.35	25.72	25.93	26.01	26.63	26.29	25.88	S
17	31.11	31.24	31.33	30.82	30.91	31.04	30.70	30.96	30.93	31.23	30.92	30.86	S
18	30.53	30.72	30.78	30.50	30.57	30.71	30.61	30.87	30.87	30.68	30.59	30.78	M to R
19	24.41	24.60	24.67	23.83	23.90	23.94				24.56	23.89		M
20	19.45	19.67	19.71	19.56	19.64	19.70				19.61	19.63		M→R
21	18.29	18.50	18.56	16.55	16.60	16.68				18.45	16.61		R
22	16.35	16.59	16.65	13.86	13.98	14.08				16.53	13.97		VR
23	18.47	18.64	18.69	17.68	17.72	17.79				18.60	17.73		VR→R
24	19.02	19.32	19.34	18.04	18.12	18.19				19.23	18.12		M to R
25	14.64	14.87	14.95	13.56	13.66	13.69				14.82	13.63		R
26	18.49	18.69	18.72	18.33	18.41	18.46				18.63	18.40		R→M
27	21.85	22.09	22.09	21.54	21.60	21.63				22.01	21.59		M to R
28	14.54	14.80	14.81	14.42	14.51	14.56				14.72	14.50		M to R
29	03.49	03.65	03.70							03.61			R to VR
30	07.78	07.94	07.93							07.89			VR

* S Slight (wave height 0.6–1.25 m); M Moderate (wave height 1.25–2.5 m); R Rough (wave height 2.5–4.0 m); VR Very rough (wave height > 4.0 m).

TABLE VI—DAILY AVERAGE STANDARD DEVIATIONS OF HOURLY PAB READINGS

Date	Adviser	Standard deviation Discovery millibars	Researcher
September 1972			
2nd		0.029	0.062
3rd		0.029	0.047
4th	0.081	0.029	0.064
5th	0.063	0.026	0.058
6th	0.064	0.028	0.067
7th	0.076	0.038	0.059
8th	0.079	0.033	0.075
9th	0.093	0.046	0.061
10th	0.081	0.045	0.048
11th	0.069	0.042	0.053
12th	0.079	0.033	0.054
13th	0.066	0.034	0.055
14th	0.069	0.036	0.050
15th	0.050	0.037	0.066
16th	0.075	0.028	0.049
17th	0.069	0.032	0.046
18th	0.098	0.049	0.052
19th	0.077	0.035	
20th	0.072	0.039	
21st	0.083	0.059	
22nd	0.112	0.100	
23rd	0.096	0.055	
24th	0.083	0.042	
25th	0.090	0.029	
26th	0.081	0.045	
27th	0.069	0.045	
28th	0.100	0.049	
29th	0.086		
30th	0.075		

The aneroids were more favourably mounted in *Researcher* (fore and aft) and this is perhaps the reason for the standard deviations being smaller than those of *Adviser*. The standard deviation of the hourly observations corrected for systematic barometer differences was nearly always less than 0.1 mb and so a typical non-systematic error after averaging the six corrected readings would be less than $0.1/\sqrt{6}$ mb. It appears then that the random effects of ship's motion and reading errors on the pressure observations were reduced to nearly negligible amounts after averaging. An attempt to assess systematic reading errors is discussed later.

Typical differences between the three pairs of PAB readings obtained hourly on each ship were about 0.2 mb, and this value may be used to give a rough idea of the accuracy with which the geostrophic wind may be calculated from the pressure data, provided that the errors due to disturbance of local airflow by the ship are ignored or else assumed to be of similar magnitude on each ship. These assumptions are not likely to be justified except in light winds.

A 10 per cent accuracy in geostrophic wind would require pressure differences between ships of about 2 mb. However, for most of JASIN the differences between ships were less than this. Clearly in these circumstances some improvement in the accuracy is required if geostrophic winds of acceptable accuracy are to be calculated. One possibility is by the use of intercalibration data obtained with the ships in close proximity.

(ii) *Effect of ship's heading on results.* Before discussing the JASIN intercalibration in detail some consideration must be given to the disturbance in the pressure field caused by the ships obstructing the airflow in their vicinity since these effects will be present when an intercomparison takes place. Calculations and measurements of flow round obstacles⁴ show that velocity deficits usually occur both upwind and downwind of obstacles, but that excesses appear round the side and above the obstruction. Thus, depending on the positioning of the static head, pressures either above or below the free-stream value may be measured. Variations of 1 m/s in a free-stream velocity of 10 m/s produce a pressure change of about 0.1 mb.

Ships taking part in any operation such as JASIN 72 have a variety of hull shapes and will thus influence the airflow in different ways; it is therefore not possible for a single static head position to be found for each ship which would at least assure pressure errors of similar magnitude for each ship and hence negligible error differences between ships. The magnitude of the errors will be much reduced if the static head is mounted a considerable distance from the main superstructure (the results of Kondo and Naito⁴ for flow across a triangular-shaped bank showed velocity perturbations of less than 10 per cent at approximately three times the bank height, and these results might be considered a rough guide for a ship lying-to (across wind), with the relevant vertical dimension now the average height of the superstructure). It had been the intention to mount the principal static heads very high on each ship in a well-exposed position but this was not found possible. Nevertheless it was hoped that the heads had been placed in positions with fair exposures where actual winds would not depart excessively from those in the undisturbed flow. Secondary heads in *Adviser* and *Discovery* were deliberately positioned in poorly exposed locations in order to obtain some idea of pressure variations over the hulls. Changes in the pressure field caused by the ships are roughly proportional to the square of the wind speed and so investigations of these changes are best carried out in at least moderate winds.

Variations of a few tenths of a millibar might be expected in winds of around 10 m/s (see above) but since the typical semi-diurnal pressure oscillation is about 0.5 mb in stationary synoptic situations it is important that any experiment should be carried out within a reasonably short space of time so that, for example, pressure changes due to variations of relative wind direction may be isolated from any diurnal or synoptic changes. In some cases it was not possible to achieve either of these criteria.

The first experiment of this nature was carried out aboard *Researcher* in winds of around 10 m/s (Table II, series 1) and occupied less than one hour. Observations were taken on 16 different relative wind directions and the initial and final pressures, obtained on the same relative bearing, were identical, suggesting only small synoptic changes. The standard deviation (S.D.) of the observations for each heading was calculated after corrections for mean differences between PABs had been made by using averages of all the observations in the series. Thus six pressure values were used to calculate the S.D.s on each heading. On average the value was about 0.05 mb and the standard deviation of the means was therefore about $0.05/\sqrt{6} \approx 0.02$ mb. The plotted mean values (Figure 1) demonstrate clearly that there are highly significant pressure changes up to 0.25 mb with changes of relative wind direction; also a small direction change may produce a relatively large pressure variation. The pressure distribution is

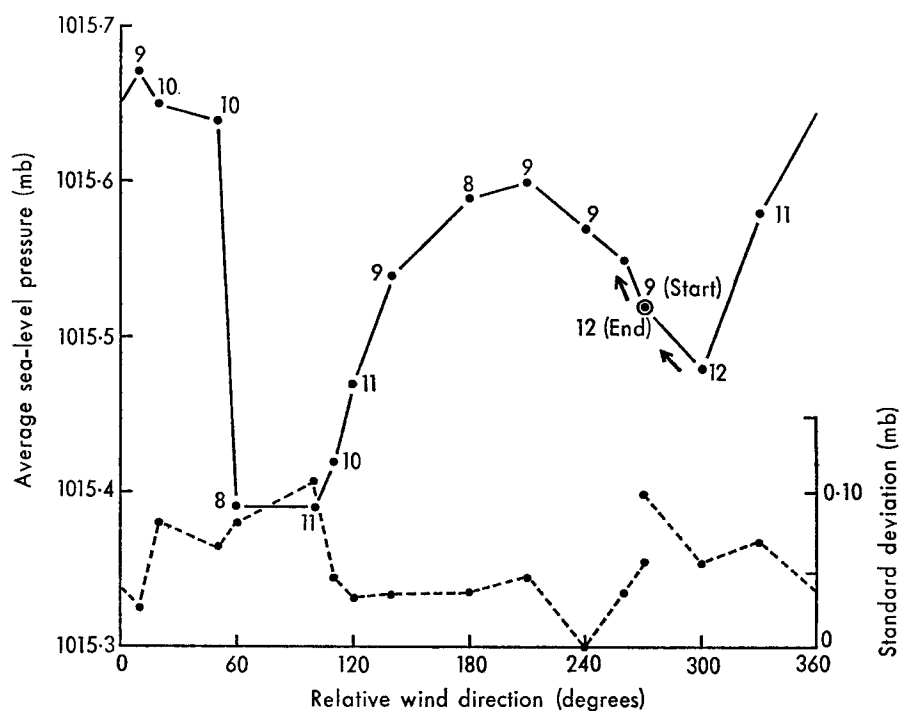


FIGURE 1—VARIATION OF MEASURED PRESSURE WITH RELATIVE WIND DIRECTION, FROM 1022 TO 1110 GMT ON 6 SEPTEMBER 1972 ('RESEARCHER')

The plotted points joined by continuous lines represent the means of 6 observations (2 from each precision aneroid barometer (PAB)). The standard deviations plotted in the lower part of the diagram are calculated from these observations after correction for systematic differences between PABs. Figures adjacent to plotted points denote wind speeds in metres per second.

consistent with stronger winds at the static head when the ship is lying-to rather than aligned alongwind. The pressure trough is more pronounced with the wind on the starboard beam and this is presumably because of the better exposure of the head for this wind direction than when on the port beam. There is also an indication of slight asymmetry in the pattern, with the highest pressure for wind along the approximate line 020–200 degrees, and this is probably due to the asymmetric position of the head. Which of the relative directions provides the 'correct' pressure is not of course revealed by the figure and must remain unknown in the absence of further data.

The second experiment aboard *Researcher* (Table II, series 2) occupied 10 hours, in winds of only 4 m/s, so although a considerable number of observations were obtained for a variety of relative ship headings it was not possible to separate variations of pressure with heading from those due to real changes in the pressure field even after applying a linear-trend correction to the observations.

The results from the two series of observations for different relative wind directions carried out aboard *Adviser* are plotted in Figures 2 and 3: a linear-trend correction has been applied to reduce the contribution from changes in the pressure field. On 10 September the mean wind speed was about 5 m/s and here the mean readings from port and starboard static heads on the mainmast agreed

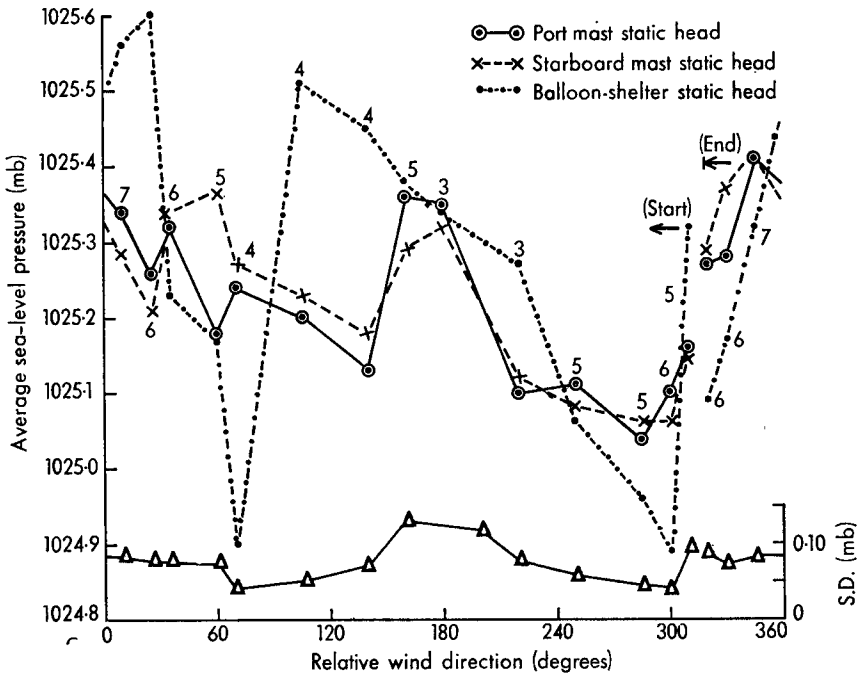


FIGURE 2—VARIATION OF MEASURED PRESSURE WITH RELATIVE WIND DIRECTION, FROM 1410 TO 1535 GMT ON 10 SEPTEMBER 1972 ('WEATHER ADVISER')

The plotted pressures represent the means of 6 observations (2 from each PAB). Figures adjacent to plotted points denote wind speeds in metres per second. The standard deviations are calculated as for Figure 1: plotted values are means of the standard deviation for each static head.

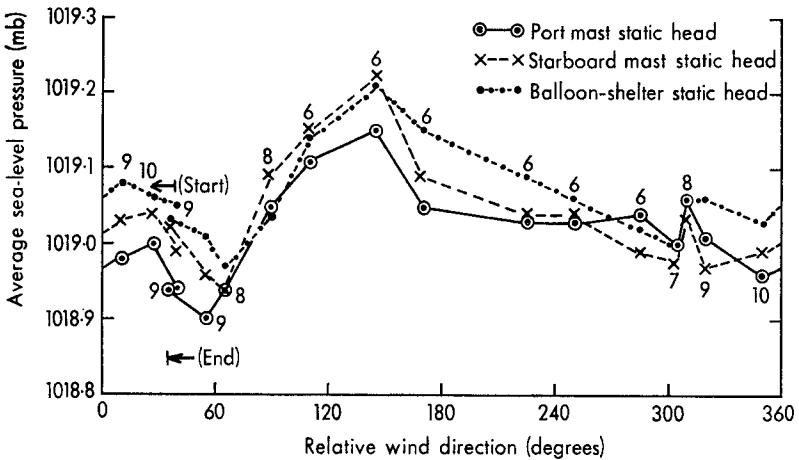


FIGURE 3—VARIATION OF MEASURED PRESSURE WITH RELATIVE WIND DIRECTION, FROM 0800 TO 0848 GMT ON 20 SEPTEMBER 1972 ('WEATHER ADVISER')

The plotted pressures represent the means of 6 observations (2 from each PAB). Figures adjacent to plotted points denote wind speeds in metres per second.

to within less than 0.1 mb on 16 out of 17 occasions, the maximum difference being 0.19 mb from a direction of 060°. The standard deviation of the 6 observations (reduced as before to a common mean pressure) for each static head was about 0.07 mb and the probable error of the mean was therefore about 0.03 mb. Differences between heads of 0.1 mb are thus highly significant. The experiment lasted nearly 90 minutes and some interference from synoptic changes of pressure must be expected but it appears that the mast-head values are higher with the ship alongwind and lower when it is acrosswind, in broad agreement with the results from *Researcher*, though the range of about 0.4 mb was higher than that found for *Researcher* in winds twice as strong. Pressures measured using the balloon-shelter static head showed very large departures from the others but showed slight similarities to the corresponding observations on 20 September (Figure 3) with peaks and troughs occurring for broadly similar relative wind directions. The wind was somewhat stronger in this latter case (about 8 m/s) but even so the port- and starboard-head values agreed to 0.08 mb or better. In contrast to 10 September the mast and balloon-shelter heads produced similar variations of pressure with wind direction. The pattern of variation for the mast heads is markedly different from that shown in Figure 3 and makes an interpretation of the results very uncertain. There is perhaps an implication that the airflow was relatively stronger when the ship was lying-to or headed into wind than when the wind was astern but the correlations appear rather weak. The probable random error of the mean was about 0.02 mb and the total variations of pressure with heading were about 0.3 mb.

The first experiment aboard *Discovery* where pressures were measured for different ship headings (Table II, series 8) was carried out in winds of about 8 m/s with both Kollsman and PAB sensors connected to the mast static head (the Kollsman readings are discussed below). The probable random error in the mean of the PAB values was about 0.02 mb for most of the experiment, rising to 0.04 mb near the end owing to increasing swell. The general shape of the PAB distribution (Figure 4) shows no obvious similarities to those obtained from *Weather Adviser* and *Researcher* for different headings and is therefore probably the result of changes in the pressure field (the experiment lasted about 150 minutes, and observation from *Adviser* showed a similar variation of amplitude at around this period: it is unlikely therefore that the broad shape of the distribution is the result of a variation of ship heading). (The results from the second experiment are included in the general discussion on the Kollsman observations on page 174.)

(iii) *Inter-ship calibrations*. Ideally the intercomparisons were required over a wide range of relative headings and wind speeds so that the routine PAB observations taken in any circumstances on the different ships could be corrected to a common standard. Because of the ship programmes and meteorological variability it was clearly impossible to do this, and the comparisons which were carried out provided rather limited information. Probably the most consistent series of observations was made on board *Adviser* and *Discovery* on 27 September (Table II, series 20, and Figure 5). Winds were between 6 and 9 m/s and the relative wind direction remained within the range 240 to 270 degrees and 360 to 020 degrees respectively for the whole series. After allowing for time differences between the observations the mean pressure difference was -0.10 ± 0.05 mb. In another comparison between these ships on 4 September (winds of 8 m/s, Table II, series 16) *Adviser*'s heading relative to wind was 360 degrees and

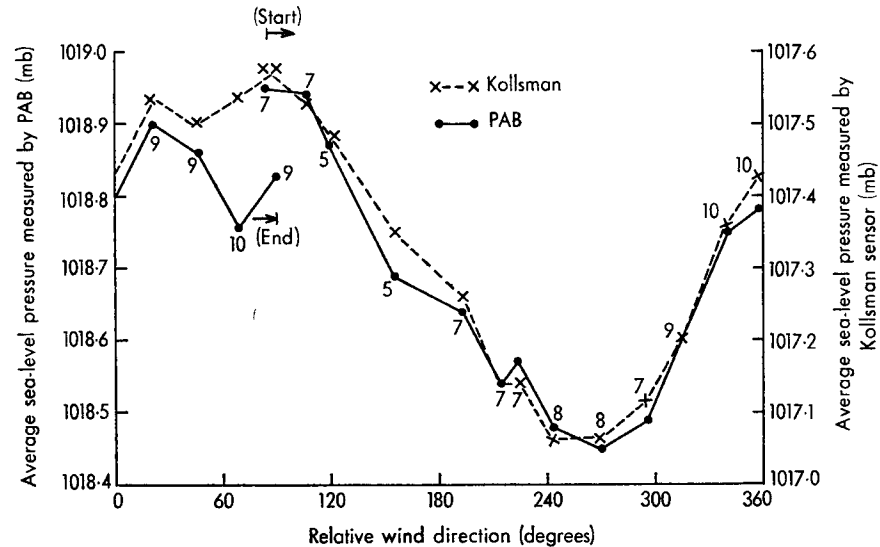


FIGURE 4—VARIATION OF MEASURED PRESSURE WITH RELATIVE WIND DIRECTION, FROM 0320 TO 0548 GMT ON 24 SEPTEMBER 1972 ('DISCOVERY')

Each plotted PAB value is the mean of 36 observations (12 from each PAB). Kollsman values are means of 100 one-second long observations made at 1.5-second intervals. Figures adjacent to plotted points denote wind speeds in metres per second.

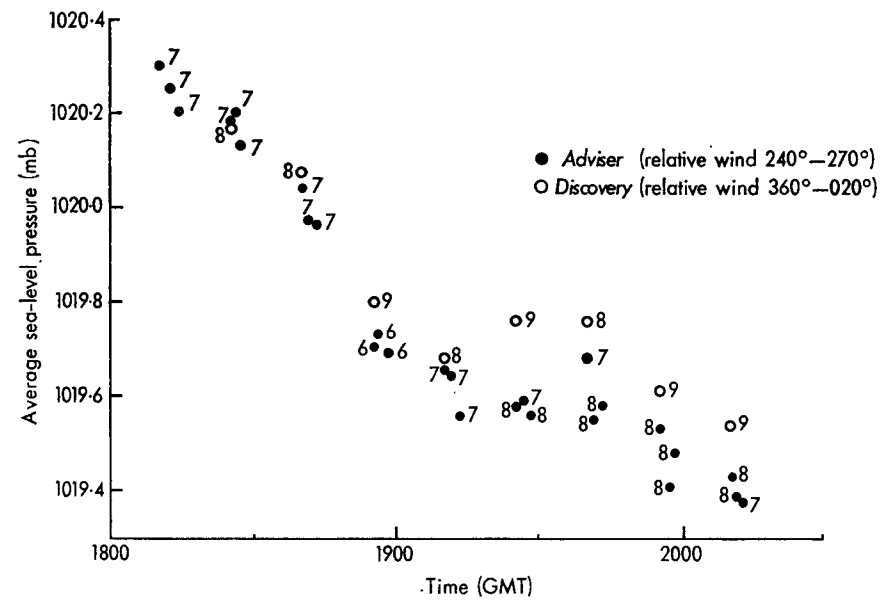


FIGURE 5—INTERCOMPARISONS BETWEEN 'WEATHER ADVISER' AND 'DISCOVERY' PRECISION ANEROID BAROMETER OBSERVATIONS ON 27 SEPTEMBER 1972

The plotted pressures represent the means of 6 observations (2 from each PAB). Figures adjacent to plotted points denote wind speeds in metres per second.

Discovery's 030 degrees. Each PAB was read nine times aboard *Adviser*, and twice aboard *Discovery*, with standard deviation of random errors 0.08 and 0.03 mb respectively: the mean difference was + 0.13 mb. The change of sign of the difference when compared to the other occasion is consistent with a change of airflow from abeam to along *Adviser*. On a third occasion on 18 September (Table II, series 19) winds were less than 3 m/s but a significant swell was present and the barometer readings showed considerable scatter especially on *Adviser*. The difference was -0.08 mb but this cannot be considered significant in view of a standard deviation for the *Adviser* observations (six readings only) of 0.16 mb.

The results of comparisons of readings made on *Discovery* and *Researcher* are given in Figures 6-8. In the first of these, carried out in winds of 5-6 m/s (Table II, series 17) three sets of simultaneous observations were taken while *Researcher* was lying-to but for *Discovery* the relative headings were 270, 360 and 030 degrees. All the *Researcher* values were lower, the average difference being 0.08 mb. Figure 1 suggests that on the basis of a square-law dependence on wind speed of the ship's influence on pressure there would be a difference of about -0.06 mb between *Researcher* observations for relative directions of 090 degrees and 360 degrees at 5 m/s. The results on 5 September suggest therefore that if the ships had both been headed directly into wind the measured pressures on each would have agreed very closely. Similar observations made on 18 September (Table II, series 19) in generally lighter winds but again with considerable variations in relative heading for *Discovery* gave a mean difference

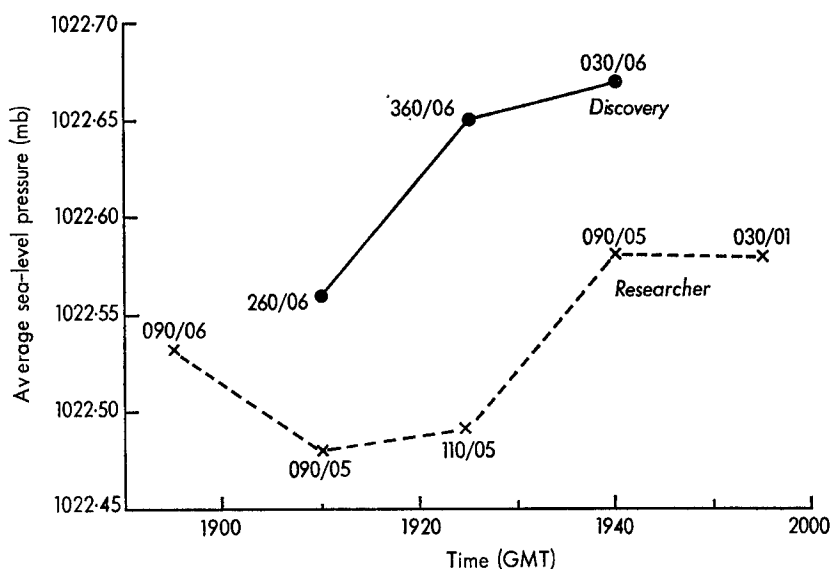


FIGURE 6—INTERCOMPARISON BETWEEN 'DISCOVERY' AND 'RESEARCHER' PRECISION ANEROID BAROMETER OBSERVATIONS ON 5 SEPTEMBER 1972

The plotted pressures represent the means of 6 observations (2 from each PAB). Relative wind direction and speed are shown in the form ddd/ff, where ddd is the relative wind direction in degrees and ff the wind speed in metres per second.

of 0.05 mb, *Researcher's* figures again being the lower. An observation from *Adviser* during this period while adjacent was about 0.08 mb lower than *Discovery's*. However, the idea that the observations made aboard *Discovery* and *Researcher* are closely comparable, with significant differences partly explicable in terms of different relative headings, is apparently destroyed by an inspection of Figure 8 which shows results from 13 September (Table II, series 18). Here the relative wind speeds were very low so that the disturbing effects of ships on the pressure field should have been negligible. However, whereas the standard deviations of *Discovery's* observations were less than 0.05 mb (each PAB was read twice at each observation time and the S.D. was calculated as before for each set of six readings after correcting to a common standard by using the observed daily mean differences between the PABs) those from *Researcher* showed much more scatter, typical S.D.s being about 0.15 mb. On the other hand reference to Figure 9 suggests that most of the contribution to the S.D.s of the *Researcher* observations was non-random, since the spread of the two individual observations made with each PAB at each time was usually small (the spread is shown by the vertical bars). There is perhaps an indication here of systematic calibration changes over a short period of time. Table V supports the view that there can occur significant changes in the daily means of readings of PABs, and Table VII, (routine PAB observations aboard *Researcher* on 13 September) suggests that changes may occur on a much shorter time scale.

TABLE VII—OBSERVATIONS MADE ABOARD 'RESEARCHER' ON 13 SEPTEMBER 1972

Time GMT	PAB 1	PAB 2 1029 mb +	PAB 3	2-1	3-1 millibars	3-2
00	0.72	0.91	1.13	0.19	0.41	0.22
01	0.55	0.83	0.75	0.28	0.20	-0.08
02	0.34	0.55	0.59	0.21	0.25	0.04
03	0.11	0.23	0.35	0.12	0.24	0.12
04	0.09	0.29	0.42	0.20	0.33	0.13
05	0.11	0.28	0.45	0.17	0.34	0.17
06	0.01	0.28	0.35	0.27	0.34	0.07
07	0.13	0.35	0.52	0.22	0.39	0.17
08	0.42	0.71	0.72	0.29	0.30	0.01
09	0.65	1.01	1.11	0.36	0.46	0.10
10	0.85	0.88	1.15	0.03	0.30	0.27
11	0.75	1.21	1.05	0.46	0.30	-0.16
12	0.53	0.75	0.67	0.22	0.14	-0.08
13	0.85	0.98	1.08	0.13	0.23	0.10
14	0.79	0.93	0.92	0.14	0.13	-0.01
15	0.55	0.73	0.82	0.18	0.27	0.09
16	0.29	0.45	0.55	0.16	0.26	0.10
17	0.09	0.21	0.22	0.12	0.13	0.01
18	0.09	0.23	0.32	0.14	0.23	0.09
19	0.09	0.18	0.35	0.09	0.26	0.17
20	-0.01	0.15	0.25	0.16	0.26	0.10
21	0.19	0.31	0.47	0.12	0.28	0.16
22	0.31	0.65	0.65	0.34	0.34	0.00
23	0.26	0.53	0.59	0.27	0.33	0.06

The extreme differences between readings from PABs 1 and 2 on this day occurred at 1000 and 1100 and were observations actually included in the inter-comparison with *Discovery*. Three observers took pressure observations during the intercomparison and it is feasible therefore that the systematic changes in differences between PABs are due to different ways adopted by individual observers of smoothing out fluctuations induced by ship motion. It is interesting

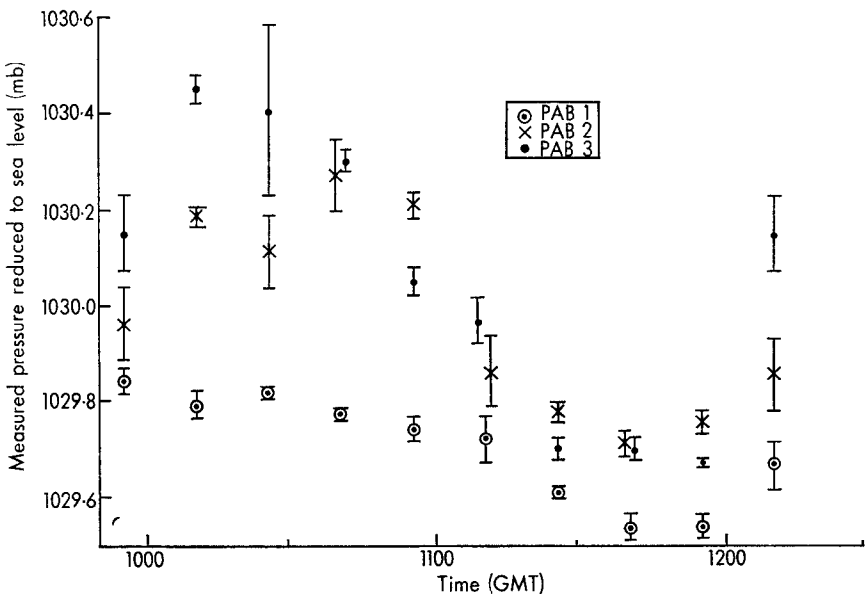


FIGURE 9—PRECISION ANEROID BAROMETER DATA FROM 'RESEARCHER' DURING INTERCOMPARISONS ON 13 SEPTEMBER 1972

The span of the individual observations and also their mean are shown for each PAB.

that the observations from *Researcher* most in apparent discord with those from *Discovery* (1010–1110, and perhaps 1210) were all made by the same observer whereas those in closest agreement (1125–1155) were made by two others. The extensive series of observations obtained with the Kollsman sensor aboard *Discovery* allow this possibility of observer bias to be explored in more detail below.

(b) *Kollsman readings.* The Kollsman device has the advantage of automatic averaging and print-out of observations. The shortest averaging time used was 1 second, and this gave an opportunity of investigating the effects of ship's motion on the output. During each of a number of 3-minute periods on 24 September (Table II, series 8) about 120 1-second averages were obtained, and the typical range of measured pressure was found to be 1.0 mb. Swell was only moderate at the time (less than 3 m) and it therefore appears that the Kollsman output is significantly affected by acceleration forces on the transducer. However, all the Kollsman data which will be discussed here were either 100-second averages or alternatively averages of observations of duration 1 second taken at 1.5-second intervals over periods of about 3 minutes and so the effects of acceleration or height displacements would have been reduced to insignificant amounts by this smoothing.

Figure 4 shows a comparison of Kollsman and PAB observations obtained by use of the same static head during the first of *Discovery's* series of special pressure measurements involving different ship headings relative to wind. The broad details of the shape of the PAB plot have been discussed already and the point of interest here is the disparity between this plot and that for the Kollsman data. Most obvious is the difference of about 1.4 mb between observations from the

two types of sensors, a difference confirmed (at least approximately) by data obtained on other occasions. Clearly the Kollsman sensor had not been properly calibrated (the Meteorological Office standard against which the PABs were checked is accurate to about 0.1 mb and is checked against a National Physical Laboratory working standard every three months). It must be hoped that the Kollsman's error was systematic and did not reflect uncertainty either in short-term stability or in the slope of its calibration curve. After elimination of the systematic difference between the sets of recordings the residual maximum differences between averaged PAB and Kollsman observations were ± 0.04 mb except for the last two pairs. Here the difference increased to about -0.15 mb, because, it is believed, of increased difficulties in reading the PABs due to an increase in swell. The trend corrections used in the plots in Figure 4 were therefore derived from the Kollsman data.

Figure 10 shows the results of Kollsman measurements using all three static heads in turn in a wind of about 4 m/s. The observations were taken over a period of about two hours when significant changes in the pressure field were occurring and the linear-trend correction which was applied almost certainly failed to eliminate these entirely from the results. The basic shape of the distributions was probably not a consequence therefore of the variable heading of the ship. The second Meteorological Office head was mounted on the port

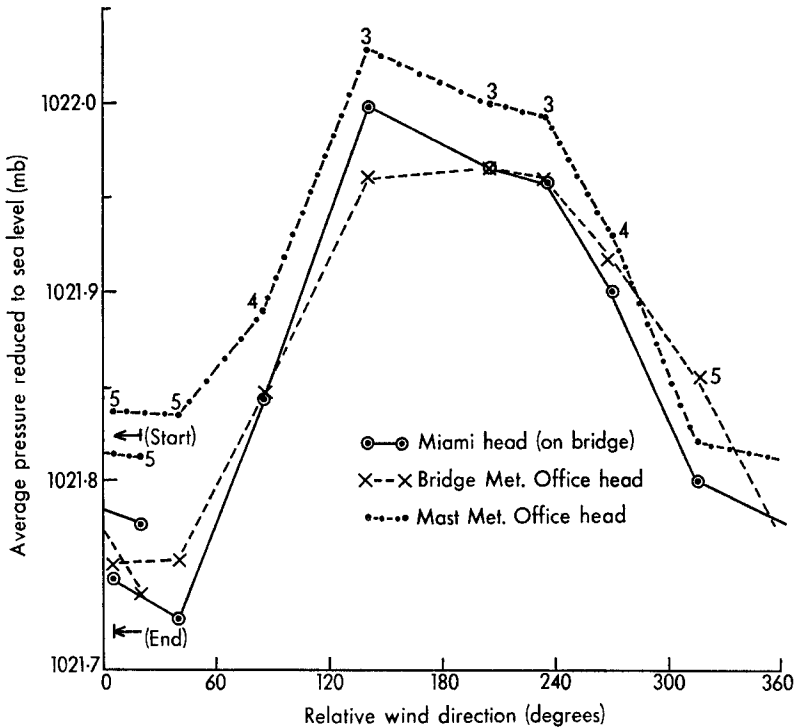


FIGURE 10—KOLLSMAN PRESSURE DATA FROM 'DISCOVERY' FOR THE PERIOD FROM 2320 GMT ON 26 SEPTEMBER TO 0132 GMT ON 27 SEPTEMBER 1972

The plotted points are 100-second averages. Wind speeds are expressed in metres per second.

guard rail of the lookout area on the monkey island, and the Miami head was positioned on the after rail of the island. Differences between pressures measured using these heads were usually less than 0.05 mb. For all observations but one the mast static head produced higher pressures, which is consistent with the stronger flow being in the region closer to the superstructure of the ship. Typical differences between mast-head and bridge-head readings were less than 0.05 mb.

Table VIII gives the differences between Kollsman and mean PAB readings for different headings on the same occasion, with both types of sensors connected to the mast static head, and also differences when the Kollsman and the single PAB on *Discovery's* bridge were connected to the bridge (Meteorological Office pattern) head. The likely random error in the first case for the PAB mean was less than 0.02 mb. There were 36 readings at each heading, with a standard deviation of about 0.09 mb after correcting for systematic differences between PABs, and this is consistent with the observed small variations in the pressure differences between the two types of sensor. A similar scatter was found for observations with the single (bridge) PAB but the differences between the mean values and the Kollsman showed substantially more variation than in the first case (Table VIII). The reason for this is not clear.

TABLE VIII—COMPARISONS BETWEEN BAROMETERS ON SAME STATIC HEAD ABOARD 'DISCOVERY', 26–27 SEPTEMBER 1972

Relative wind (approximate) degrees	(Mast Head)		(Bridge Head)	
	Kollsman minus average of PABs	Difference from mean	Kollsman minus bridge PAB	Difference from mean
		millibars		millibars
360	−1.211	0.002	−1.155	0.040
315	−1.210	0.003	−1.277	−0.082
270	−1.177	0.036	−1.173	0.022
225	−1.226	−0.013	−1.249	−0.054
180	−1.194	0.019	−1.106	0.089
135	−1.209	0.004	−1.187	0.008
090	−1.225	−0.012	−1.168	0.027
045	−1.240	−0.027	−1.149	0.046
000	−1.221	−0.008	−1.287	−0.092

Data obtained on the 28th (Table II, series 14) provided a further opportunity to study the effects of different positions of static heads on measured pressure. Here all three heads were used in turn, usually at 5-minute intervals. The relative wind speed changed markedly during the period, from about 15 m/s during the first part to 6 m/s towards the end. Mean pressures for the two wind speeds are given in Table IX.

TABLE IX—KOLLSMAN OBSERVATIONS USING THREE STATIC HEADS ON 28 SEPTEMBER 1972 (SERIES 14)

Mean wind speed m/s	Relative direction degrees	Mean pressures measured by		
		Bridge (Meteo- logical Office pattern) head	Bridge (Miami pattern) head	Mast Static head
			millibars	
15	010	1012.18	1012.10	1012.72
6	010	1013.05	1013.04	1013.14

The results confirm others discussed earlier, that is to say there were relatively small differences between bridge-mounted heads but significantly higher pressure at the mast static head particularly in the period with strong wind. As might be expected the difference between mast and bridge static-head values is roughly proportional to the square of the wind speed, and its magnitude suggests that (if Bernoulli's equation can be applied) the wind over the bridge static head is about 20 per cent higher than that at the mast static head.

During the period from 9 to 23 September (Table II, series 5) Kollsman readings were taken at 5-minute intervals using the Miami head, and therefore although the data cannot be directly compared with the routine PAB observations in order to assess, for example, the relative stability of the two types of transducer, they do provide an opportunity to investigate the effects of observer bias on the PAB data. Thus in spite of differences between the two sets of data varying with time, owing, for example, to the variation of the ship's heading, or relative wind speed, the number of hourly observations is large enough (approximately 350) for these variations to be distributed reasonably uniformly between the three observers involved in the PAB observations. The results are given in Table X in the form of means and standard deviations of differences between Kollsman and PAB readings for each of the three observers involved in the PAB observations. Observer 2 made observations with the smallest standard deviation and was presumably the most effective in averaging out the effects of ship's motion on PAB readings. Data obtained by Observer 3 had the largest scatter but otherwise they were closely comparable in the mean with those from Observer 2. In contrast, Observer 1 produced data which showed systematically higher values for each of the PABs, suggesting that he was using a reading technique somewhat different from that adopted by the other two observers.

TABLE X—OBSERVER BIAS IN PAB RESULTS (9–23 SEPTEMBER)

PAB	Differences between PAB and Kollsman readings					
	Observer 1		Observer 2		Observer 3	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
	<i>millibars</i>					
1	1·349	0·236	1·309	0·216	1·288	0·252
2	1·394	0·249	1·345	0·227	1·347	0·278
3	1·491	0·236	1·439	0·219	1·437	0·264
Means	1·411	0·240	1·364	0·221	1·357	0·265

During the period 23–25 September (Table II, series 6, 7 and 9) the Kollsman and PABs were connected to the mast static head and the resulting observations allowed a further investigation of observer bias. The results appear in Table XI. Again the scatter was smallest for Observer 2 and largest for Observer 3 but in contrast to the results given above the highest average values were obtained by the latter. However, because of the relatively small number of data the largest difference between the means is significant to no better than about the 30 per cent level.

TABLE XI—OBSERVER BIAS IN PAB RESULTS (23–25 SEPTEMBER)

Difference between mean PAB and Kollsman readings					
Observer 1		Observer 2		Observer 3	
Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
	<i>millibars</i>				
1·324	0·061	1·321	0·056	1·342	0·067

(On page 169 it was pointed out that one of the intercomparisons involving *Researcher* and *Discovery* produced some fairly strong evidence for substantial barometer errors apparently caused by the way in which one of the observers smoothed out the effects of ship's motion while he noted the PAB readings. In Table XII the mean values of the routine observations obtained by each observer aboard *Researcher* during JASIN 72 are listed. Each mean was calculated from about 120 observations, spread more or less evenly throughout the day (6-hour shifts were worked) so that the differences between means are expected to be affected to only an insignificant extent by normal diurnal pressure variations. Observer 2 appears to have made readings about 0.2 mb higher than the other two; he also made the anomalous observations in the intercomparison between *Discovery* and *Researcher*, which therefore appears to be subject to observer bias rather than short-term sensor drift.)

TABLE XII—MEAN VALUES OF OBSERVATIONS MADE ABOARD 'RESEARCHER' FOR EACH OBSERVER

Observer	1	2	3
Mean (mb)	1026.38	1026.60	1026.46

Conclusions. Wind speeds were generally low during JASIN 72 and it was therefore not possible to carry out all the shipboard pressure experiments in conditions ideal for revealing the ship's disturbance of the local pressure field, but a number of useful results have emerged. In particular the Meteorological Office PAB appears not to be reliable to better than about ± 0.2 mb. However, the relative accuracy, found by comparing the daily mean values for each PAB on each ship separately, was with the exception of one sensor on *Researcher* within the range ± 0.1 mb.

Intercalibrations with ships in close proximity are clearly useful in giving data which may be used to reduce relative pressure errors *between* ships but necessarily demand that the ships involved take up orientations with respect to wind which are used in the routine observations since the ship-induced perturbation of the pressure field has been demonstrated to vary significantly with relative heading. However, the perturbation depends also on wind speed, and a range of wind speed would usually be achieved during an intercalibration only by ships heading into wind at various speeds, thus limiting the chosen relative direction to 360 degrees. On the other hand the present results support the idea that the perturbation is roughly proportional to the square of the wind speed and so, provided that the intercalibrations are carried out so as to include observations in *zero* relative wind, the corrections for the different headings can be deduced for speeds other than those occurring at the time of intercalibration. Clearly the intercalibration needs to be carried out in the shortest possible time (to avoid complications due to changes in the pressure field) and in strong winds (where perturbations are large).

The results have demonstrated fairly conclusively that observers differ in the way in which they smooth out the effect of ship motion on the PAB values, at best producing different amounts of scatter and at worst systematic differences in the mean. The solutions here (in the absence of modifications to provide automatic averaging and print-out) are to establish a uniformity of reading standard by training, to have all observers participating in intercalibrations, and to mount PABs with fore-and-aft orientations in order to decrease effects of

ship's motion. The results from *Discovery* demonstrated that in a larger ship, even with athwartship orientation of PABs the observer differences may be as small on average as 0.05 mb.

The Kollsman sensor on *Discovery* appeared to function satisfactorily: however, it was surprising to find a calibration error greater than 1 mb. There was no evidence of any drift; for example the mean difference between PABs and Kollsman for series 5, and for series 6, 7 and 8 were respectively 1.38 and 1.33 mb: the small disparity in these values is explicable in terms of the two different positions of static head used in series 5. The 100-second averaging capability of the device was invaluable though it should be pointed out that the multiple-recording technique used for the PABs can also be very successful in reducing fluctuations of pressure due to ship acceleration.

As expected the experiments have not given much useful information on the most advantageous placing of the static heads. It is believed that the effects of ship's influence cannot be satisfactorily reduced by any particular, uniquely specifiable placing of the static head and so the best chance of making accurate pressure measurements may come from applying corrections to observations using the air velocity at the static head and an estimated 'free-stream' velocity at the same height in Bernoulli's equation. The first velocity might be measured fairly easily with a small cup anemometer and the second could be obtained with sufficient accuracy from an upward extrapolation of speed measured on an adjacent meteorological buoy. The type of buoy is stressed here because such an anemometer would have to be well exposed in order to measure speeds to within the required accuracy of a few per cent, and thus the buoy would have to be relatively uncluttered.

Acknowledgements. Installation of the PABs and static heads was carried out by D. Winters and D. R. Davies. Thanks are due to the Masters and crews of R.R.S. *Discovery*, m.v. *Researcher* and O.W.S. *Weather Adviser* for their co-operation and to the observers for their diligence in obtaining the PAB data.

Professor E. B. Kraus of the School of Marine and Atmospheric Science, University of Miami, provided the Kollsman sensors and made available data obtained by them.

The Institute of Oceanographic Sciences supplied on magnetic tape all the routine meteorological data from JASIN (including PAB observations).

Miss S. A. Matthews carried out most of the data processing.

Particular note should be made of the efforts of Dr R. T. Pollard, including the co-ordination of the Kollsman and PAB measurements on *Discovery*, and arranging the supply of Kollsman data and the re-formatting of data on magnetic tape.

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NOCTILUCENT CLOUDS OVER WESTERN EUROPE AND THE ATLANTIC DURING 1974

By D. H. McINTOSH and MARY HALLISSEY
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Positive observations of noctilucent clouds (NLC) between 26 May and 8 August 1974, made by the network of observers associated with the Data Centre at Edinburgh, appear in Table I. This network, which is associated with the Aurora Survey, consists of professional meteorological staff (on land and at sea) in Great Britain and Ireland, voluntary amateur observers, most of whom are members of the British Astronomical Association, voluntary observers in Denmark and Norway and aircrew personnel of British and Dutch aircraft. The Survey is financed by a grant from the Royal Society, with additional finance from the Meteorological Office. The data after analysis are sent to the other World Data Centres at Tartu and Toronto; reprints of this report are sent to scientists at home and abroad who are interested in the study of the phenomenon, and information is readily available, along with series of photographs, to workers in the field.

The dates in Table I cover the period of optimum viewing of the clouds between geographic latitudes 50° and 60°N. The period of time during which the clouds were observed appears in the second column, and should not necessarily be taken as the full extent of the display; this is stated where possible, but it is obviously difficult, particularly for voluntary observers, to record a display to the point of disappearance. Brief notes on the displays appear in the third column. In the remaining columns details of the relevant station co-ordinates are listed to the nearest half degree, and where known the maximum elevation and limiting azimuths of the observed cloud.

TABLE I—DISPLAYS OF NOCTILUCENT CLOUDS OVER WESTERN EUROPE AND THE
ATLANTIC DURING 1974

Date— night of	Times	Notes	Station position*	Time	Max. elev.	Limiting azimuths
	UT			UT		degrees
26/27 May	2120–2150	Bands, billows and whirls with veil background extending almost to zenith in NNW.	51N 01E	2120	80	290–040
29/30	2125, 2150 0150	Veil to 12° and outlining bank of tropospheric cloud, with two separate bright patches of NLC at higher elevation. At 0150 possible sighting from southern Ireland.	53N 0·5E 52N 10·5W 51N 01E	2150 0150 2125	60 40 20	330 360–045 320–010
3/4 June	2325	NLC suspected visible south-west Scotland.	55N 04·5W			
7/8	0045–0120	Bright banded area of NLC seen north-east Scotland and from OWS <i>Weather Adviser</i>	58N 14·5W 57N 02W	0100 0045	20 14	360–020 360–020
8/9	0016–0350	NLC suspected visible 2300 south-west Scotland. Identified from North Wales after midnight as medium bright band low above N horizon. Two bands visible 0030 and 0045. Visible central England 0150, ill-defined and faint.	55N 04·5W 53·5N 03W 53N 01·5W	0016 0030, 0045 0150 0310	3 4 15 20	345–360 360
9/10	2130	Bands and whirls in complex formation against veil background centred on Vega; bright banded area also against veil background to 20° in NNW. Southern edge of veil beyond observer's zenith.	51N 01E	2130	130	315–090

* To nearest 0·5 degree.

TABLE 1—continued

Date— night of	Times	Notes	Station position	Time	Max. elev.	Limiting azimuths
	UT			UT	degrees	
12/13 June	2115–0400	NLC first seen south-west Scotland. Bands seen central Scotland. 2250–2325, only slight eastward movement with sun until obscured 2325. From OWS <i>Weather Monitor</i> NLC described as ill-defined but with clear eastern edge, fading S-N from white to sepia at horizon.	56°5'N 07°W 56°N 04°5'W 55°5'N 07°5'W 55°5'N 04°5'W 54°N 10°W 54°N 01°5'W 53°5'N 09°W	0145 2250 0050	30 16	045 340–010 325–040
		From eastbound KLM aircraft report of NLC 0200–0400; veil, bands and billows; simultaneous auroral appearance 0200 over W Atlantic.	53°N 51°W 54°5'N 36°5'W 55°N 25°W	0200 0300 0345	1 5 30	045
13/14	2345 0030–0100	Faint, diffuse bands of NLC; little movement. Upper band brightening but later obscured by moonlight.	55°N 04°5'W 54°N 0°5'W	0030 0055	13 15	345–025
15/16	2135	Bright veil to approx. 15° elev. with detached bright patch in NNW showing band structure.	51°N 01°E	2135	20	315–045
19/20	2247	Queried reports of NLC possibly to high elevation in NE from north-east Scotland and north-west England.	57°N 02°W 53°5'N 03°W			
20/21	2110–0130	Extensive though not brilliant display. Widely reported over Great Britain and Ireland, most clearly from central Scotland and northern Ireland. At 2300 large area of parallel bands and transverse billows detected. After midnight these appeared from northern Ireland and central Scotland as two wide and bright bands, and at 2330 from southern Ireland as two intersecting bands.	57°N 02°W 56°5'N 03°W 56°N 04°5'W	2315 2354 0005 0046 2140 2230 2300	3 38 44 44 20 30 45	315 290–310 290–310 280–350 330–010 310–330 290–330
		A photograph of the clouds from central Scotland at 0040 shows faint band and billow formation and clearly indicates their extension almost to the zenith.	55°5'N 07°5'W 55°5'N 05°5'W 55°5'N 04°5'W 55°5'N 03°W 55°N 04°5'W 54°5'N 08°W 54°5'N 06°W 53°N 08°W 52°5'N 09°W	2300 2345 2355 2400 0001 0005 0010 2330	14 15 20 20 10 9 12 5	320–350 320–350
21/22	2330	Possible NLC; no detail.	55°N 04°5'W			
22/23	2145–2350	Possibly faint NLC.	55°N 04°5'W			
24/25	2140–2155 2345–0200	Early sighting partly obscured by low tropospheric cloud. After midnight southward extension with veil, bands and billows identified.	58°5'N 03°W 56°5'N 07°W 56°5'N 03°W 55°5'N 07°5'W	2140 2155 0043 0005 0050 0150 0105 0247 0333	10 2 20 32 12 42 15 1 2	360–020 360 315–010 340–050 330–360 340–030 340–035
25/26	0247–0420	From eastbound British Airways aircraft report of simultaneous appearance of aurora and NLC, the latter at very low elevation. Horizontal bands of varying brightness and fibrous 'mares' tails' structure identified.	55°5'N 04°5'W 48°N 50°W 50°N 40°W	0105 0247 0333	15 1 2	330–360 340–030 340–035
29/30	2345, 0145	NLC seen as bright band from northern England. No other details.	56°5'N 07°W 55°5'N 01°5'W 54°N 04°5'W	2345 0145 0100	9 15 10	015–030 360–030 360, 020
3/4 July	2350–0200	Clear sightings from central and north-west Scotland identify bands and whirl formation; whirl patches very bright 0115. Possible sighting from central England hampered by tropospheric cloud.	57°5'N 07°5'W 56°5'N 07°W 56°5'N 03°W 53°N 01°5'W	0050 0100 0150 0100 2350	11 16 5 15	340–070 350–035 330–090 360
5/6	0700–0800	From aircraft over western North America report of simultaneous aurora and bands of NLC; aurora associated with large-scale solar activity and reaching low latitudes. Both phenomena faded with daylight 0800.	50°N 07°W 51°N 04°W 52°5'N 90°W	0700 0725 0740	1 7 14	335–045 045 310–100
6/7	0030–0210	After clearance of heavy cloud at 2400 NLC patches of varying intensity visible north-east Scotland; faded by 0210.	57°5'N 03°5'W	0100	22	310–050
8/9	0130–0230	Early sighting of faint bands to high altitude seen from northern England. Later sightings from OWS <i>Weather Surveyor</i> , north-east Scotland and northern England; described from northern England as 'brilliant veil' above low band of tropospheric cloud.	57°5'N 03°5'W 55°N 10°5'W 54°N 01°W 53°5'N 03°W	0130 0215 0145 2200	28 35 19 20	045 350–022 345–030 330–360

TABLE I—*continued*

Date— height of	Times	Notes	Station position	Time	Max. elev.	Limiting azimuths
	UT			UT		degrees
9/10 July	2150-0250	First sighting of display in NW quadrant from central Scotland; brightest to W with fibrous structure stretching to N up to 50°. At 2215 in area to W zenith of station in north-east Scotland structure described as thickened southern edge with series of billows stretching towards north. Clouds now seen from northern England. At 2230 from central Scotland bands seen to appear in north-east as well as higher patch in north-west. After midnight formation of further bands in NNE, and structure clearly billowed at 0037 up to 15° as seen from north-east Scotland; at 0130 herring-bone formation visible. At 0200 patches of featureless cloud visible north-east Scotland up to 75°. Cloud suspected visible central England 0250.	57N 02W 56°5'N 03W 56°5'N 02°5'W 56N 04°5'W 56N 03W 54N 01W 53°5'N 03W 53N 01°5'W	2215 0200 2215 2250 2230 2240 2150 2210 2220	70 75 40 25 40 50 25 16	290-360 290-350 315-360 320-040 310-060 315-360 340-010 325-020
10/11	2115-0300	Clouds observed through binoculars 2115 in Denmark as faint bands NNE-NE and by 2205 through gaps in tropospheric clouds. From north-west England at 2230 seen as delicate bands and billows. In north-east Scotland at 0105 parallel bands clearly distinguished almost to zenith NW-NNE.	57N 02W 56°5'N 03W 55°5'N 03W 55N 14°5'E 54°5'N 06W 54N 04°5'W 54N 01W 53°5'N 03W 57°5'N 07°5'W 57N 02W	2340 0025 0105 0100 2250 2330 2240 0135 0150 2230 0150 0015 0152 0215	10 15 70 16 5 10 20 5 7 19 60 50 90	300 335-045 320-085 360-045 340-360 330-340 350-020 345-035 350-360 350-015 030-060 290-020
11/12	2150-0300+	Presence of NLC suspected south-west Scotland 2150. Seen northern England 2230 as bright bands. Photographs and sketches show bands, billows, whirls with wisps to high elevation. Development noted 0100-0140 of longitudinal position of bright band in NW. At 0145 whole display reported from north-east Scotland to be moving southwards so that northern edge of cloud appeared to be 5° clear of N horizon. NLC visible in northern Ireland and north-east Scotland to 0300 when it was also reported visible from aircraft over eastern Atlantic.	56°5'N 07W 56°5'N 03W 55°5'N 01°5'W 55N 04°5'W 54°5'N 06W 54N 01W 53N 15W 56°5'N 03W 55N 04°5'W	2330 0030 0100 0240 2336 0009 0100 0020 0145 0010	10 15 25 90 8 20 17 4 8 7	340-020 350-030 350-060 360-070 350-020 020 010-020 340-020 330-020
12/13	2310, 2315	Faint NLC seen from south-west Scotland; two patches of the cloud also reported from central Scotland.	56°5'N 03W 55N 04°5'W	2315	19	345
13/14	2140-2215, 2250	Unspectacular appearance of NLC seen from south-west Scotland and western Ireland. No forms discernible.	55N 04°5'W 54N 09W	2140 2250	15 15	360-045 345
14/15	0050-0125	Very bright patch of NLC seen from north-east Scotland with billow formation central to banded areas. Diffuse and weak band of NLC suspected to be in zenith of this station.	57N 02W	0100	25	320-035
15/16	2205-0035 0230-0400	Extensive and comparatively bright NLC seen from central Scotland to elevation 70+°, few strands of the cloud up to 90°. Bands, billows with single layer veil formation overhead. Pilot of KLM aircraft observed brilliant blue NLC during Atlantic crossing 0230-0400 with unchanging elevation 5° to 10°. Simultaneous aurora recorded 0230-0400 from this aircraft.	56N 04°5'W 53°5'N 58W 54°5'N 30W	2300 0230 0400	90 10 10	
17/18	2340-0245	Widely reported and extended display inspiring many sketches and drawings. Most southerly reporting station records 'beautiful display of bright green closely packed and intricate bands and billows. Although of limited altitude the display was very bright and the most satisfying I have so far observed'.	60N 01W 59N 03W 56°5'N 07W 56°5'N 03W 55°5'N 07°5'W 55°5'N 05°5'W	0100 0015 0115 2340 0150 0145 2350 0145 0215 0100	30 18 23 10 15 9 4 6 5 5	330-040 320-055 330-065 350-010 340-030 360 360-040 360-045 350-070 345-045

TABLE I—continued

Date— night of	Times	Notes	Station position	Time	Max. elev.	Limiting azimuths
UT						
17/18 July continued						
			54°5'N 06°W	0120	4	355–050
				0150	4	020–060
			54°5'N 01°5'W	0105	5	330–005
				0154	6	357–020
			54°N 04°5'W	0145	15	350–050
			54°N 01°W	0050	3	360
			53°5'N 03°W	2350	3	350–005
				0200	6	350–050
19/20	2225–0030	Static display of S-shaped band of NLC with faint transverse billows.	56°5'N 03°W			
			56°5'N 02°5'W			
			52°5'N 07°5'W	2245	5	360
21/22	2150–0315	Excellent photographs (a) from Denmark show the early stages of the display with veil, bands and billows: (b) from England show the clouds after 0200 with very bright cloud mass, banded structure and billows to NNE, and indication of faint cloud to higher elevation. This higher-elevation NLC also suspected from north-west England.	57°N 02°W	2110	30	270–360
			56°N 10°E	2245	15	–045
			53°5'N 03°W	2315	20	350–030
			53°N 0°5'E	2150	5	015
				0220	7	335–040
				0302	8	350
22/23	2330–0210	Observers at many stations prevented at times by tropospheric clouds from seeing obviously extensive NLC. Fibrous veil and well-defined bands, billows and whirls identified. At 0100 cloud field seemed to move eastwards; sharply defined horizontal billows changed to appear by 0114 transverse and diffuse.	60°N 01°W	2350	90	
				0050	25	345–060
			59°N 03°W	0100	14	330–050
			58°5'N 03°W	0050		315–045
			57°N 02°W	0100	5	060
				0140	18	340–050
			56°5'N 03°W	0045		020–060
			55°5'N 01°5'W	0145	10	350–020
			55°N 03°W	0045	6	350–020
				0130	9	350–040
			54°N 01°W	0001	2½	360–030
			53°5'N 01°W	0220		
			53°N 01°5'W	0140	5	020–050
23/24	2350–0300	Less widely reported display, though bands and billows clearly defined. Simultaneous appearance of aurora reported from OWS <i>Weather Reporter</i> . Whirl forms observed from central Scotland.	59°N 19°5'W	0050	8	350–030
			56°5'N 07°W	0200	14	360–050
			56°5'N 03°W	0145	11	350–070
				0245	15	020–040
			56°N 04°5'W	0200	12	340–030
			55°5'N 04°5'W	0200	20	040–080
			55°5'N 01°5'W	0140	3	350–040
				0200	5	
26/27	2355–0135	Small traces of NLC moved sufficiently far south for bands to be identified; brightest 0050.	60°N 01°W	0035	8	340–020
				0050	5	340–020
27/28	2400–0220	NLC seen mainly as fibrous structure with more intense patches. Bands and billows discernible from north-east Scotland with southwards extension of cloud area in approaching dawn.	59°N 03°W	0150	15	360–020
			58°5'N 03°W			
			57°N 02°W	0008	20	300–070
				0147	25	330–020
			56°5'N 07°W			
			56°5'N 03°W	0130	5	360
				0145	10	020–040
28/29	2325–0220	Faint display; little structure. Faded into dawn 0220.	57°N 02°W	2350	3	020
				0050	5	045
			56°N 03°W	0200	5	
			56°5'N 03°W	2400	1½	360
				0130	3	360–015
29/30	0050–0235	Narrow bands distinct against veil background of very-low-elevation NLC.	59°N 03°W	0050	15	020–030
			56°5'N 03°W			
			55°5'N 04°5'W	0150	5	350–040
			55°5'N 03°W	0145	5	355–015
				0215	8	
			55°N 03°W	0140	6	340–040
				0220	8	350–040
			54°N 01°W	0145	1½	360–020
31 July/ 1 Aug.	2215	Possible sighting from south Norway. Clouds bright near NNW horizon and stretching almost to zenith.	59°N 09°E	2215	58	340–020
1/2 Aug.	2300–2330 0030	Possible sighting of NLC from North Wales; low bright band near N horizon, sepia tinged.	53°5'N 03°W	2300	1	360
2/3	0300	Distant NLC seen as very-low-elevation 'lenticular' patch.	58°5'N 03°W	0300	3	325
4/5	0050	NLC patch; no details.	59°N 03°W	0050	20	350–010
7/8	2100–2140	Bright and short-lived appearance of banded NLC seen from Denmark. Westward movement with decreasing brightness and elevation.	56°N 10°E	2100	7	340–045
				2115	5	

The clouds were reported to the Laboratory on 41 nights between 26/27 May and 7/8 August, 22 being during July, with an almost unbroken series from 5–24 July. Although information for the 'blank' nights of this series has been carefully examined, it is not possible to conclude firmly whether or not clouds were present. A single observation of possible NLC on 7/8 July was regarded as doubtful because of reported clear conditions at stations in the area at that exact time; reports for 16/17 July show mixed cloudiness, but 18/19 and 20/21 July show almost 100 per cent cloud cover. Many observers identify the clouds at times of large amounts of tropospheric cloud, whereas unless perfectly clear conditions exist at several stations throughout the twilight period, visual evidence of their absence is incomplete—factors which form only a part of the complex problem of calculating probability of occurrence.

Numerically, the peak of the observing period in 1974 was again in the first half of July and not, as in 1973,¹ in the latter part of June. A 10-year chart, which it is hoped may be published at a later date, shows a more marked contrast between these two half-months in the years 1967 and 1974.

Simultaneous appearances of NLC and aurora were reported on five occasions, four reports came from aircraft personnel and one from a Weather Ship observer. On 12/13 June, the pilot of a KLM aircraft noticed the NLC when observing details of the aurora over the western Atlantic. The clouds were unfamiliar to him, but realizing their unusual nature and having roughly computed their great height, he sketched their structure during two hours of transatlantic flight.

We trespass on the territory of another Data Centre with the report of simultaneous aurora and NLC on 5/6 July, when the aircraft concerned was *en route* from Los Angeles. The extensive equatorwards spread of the aurora was part of the activity associated with the solar outburst of early July. The flying height of the aircraft was 33 000 ft, and when first noticed the NLC was seen on the pilot's horizon.

The number of nights when NLC was reported overhead in southern England, i.e. two, is the same as during 1973. The clouds were reported overhead in the mainland of Scotland on a further six nights.

Among photographs taken were series from Aberdeen for 9/10, 10/11, 11/12, 22/23 and 28/29 July; from Dundee for 11/12 July; from West Raynham for 21/22 July and from Alrø, Denmark, for 21/22 July.

The help of the many observers who have sent reports and sketches to the Data Collection Centre at the Balfour Stewart Laboratory, Department of Meteorology, University of Edinburgh, is gratefully acknowledged.

REFERENCE

1. MCINTOSH, D. H. and HALLISSEY, MARY; Noctilucent clouds over western Europe during 1973. *Met Mag, London*, 103, 1974, pp. 157–160.

REVIEWS

Automatic air quality monitoring systems (Proceedings of the Conference held at the National Institute of Public Health in Bilthoven, The Netherlands, 5-8 June, 1973) edited by T. Schneider. 250 mm × 170 mm, pp. xvi + 267, *illus.*, Elsevier Scientific Publishing Company, Jan van Galenstraat 335, Amsterdam, The Netherlands, 1973. Price: Dfl. 42.

In common with many conference proceedings, this publication contains papers of variable scientific content, degree of complexity and standard of presentation.

The purpose of the symposium was to exchange knowledge on existing and planned automated air-quality monitoring systems and the analysis of air pollution data. It contains 18 papers almost entirely concerned with the monitoring of urban pollution. They can be divided into the following categories:

One paper describes the measuring techniques applicable to automated networks; two give basically historical and organizational accounts of the United States and United Kingdom sampling networks; three describe planned or operating automated sampling systems and one describes the results obtained from such a network.

A further seven papers deal with data analysis and presentation and urban pollution modelling and one paper is concerned with the mesoscale and large-scale transport of sulphur dioxide and sulphate particles.

In addition to the papers, the conference discussions have been reproduced. These make interesting reading and help considerably in placing the papers in context. Unfortunately discussion does not always follow the papers in the appropriate place. This causes great difficulty in following the discussion in some cases.

Although many of the papers make reference to the importance of meteorological measurements and forecasting in air pollution monitoring, none discusses meteorological aspects in any detail. The claim is made several times that 'real time' information on pollution concentrations is required as well as meteorological information if forecasts of pollution levels are to be made. However, it seems that forecasts on time scales as short as fractions of an hour are contemplated. When forecasting longer-period average concentrations the requirement for 'real time' pollution data seems less important.

The papers and particularly the discussions in this volume highlight the varied approaches to pollution control adopted by different countries and the consequent need for a range of air monitoring systems. The requirements vary all the way from a continuous flow of 'real time' pollution data through continuous measurement but delayed presentation to the measurement of daily, weekly or monthly averages of concentrations.

The discussion of these different philosophies of pollution control sets the technical problems and costs of the various monitoring systems in context.

To sum up, this volume contains interesting accounts of pollution measurement systems and some illuminating discussion of the varied control philosophies. It contains little of direct meteorological interest.

Energy fluxes over polar surfaces. Proceedings of the IAMAP/IAPSO/SCAR/WMO Symposium, Moscow 3–5 August 1971. WMO Technical Note No. 129 (edited by S. Orvig). 270 mm × 210 mm, pp. vii + 299, illus., Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1973.

As indicated in the subtitle, this volume is a collection of papers presented at a symposium. The 14 papers available here encompass a wide variety of topics ranging from micro-meteorological field work to numerical atmospheric modelling on a global scale and are of varying quality and standard.

Almost inevitably in the first two sections concerning detailed energy fluxes over land-ice and sea-ice surfaces there is a certain amount of repetition as fundamental micro-meteorological principles are restated in successive papers. In two of these papers and in one dealing with spectral energy distribution in short-wave fluxes there are apologies either for instrumental troubles or for data deficiencies. These, together with some of the consequent stop-gap assumptions, detract from the value of the work. Nevertheless the values of fluxes that are given seem reasonable enough, and add to the limited data already available. The ordinariness of these two sections is relieved by an original and fascinating discussion of the energetics of the Antarctic surface wind (U. Radok), the dominant features of which are compared with those of the trade winds. The author concludes that the surface-wind system is an essential part of the whole Antarctic circulation, even though this poses problems of identifying the control and feedback mechanisms.

The section on regional large-scale energy fluxes is more satisfactory and contains useful matter-of-fact papers dealing with the albedo of pack-ice, the surface heat balance and climate of the dry valleys in Antarctica, and the synoptic energy budget of the Beaufort Sea. In this last paper Vowinckel and Orvig present computations of data relating energy fluxes to the percentage ice-cover, which should provide useful boundary conditions in some atmospheric-numerical models.

The next section considers global studies of large-scale energy fluxes, and continues the theme of the effect of ice-cover in a paper on the numerical simulation of the influence of Arctic sea-ice on climate. The authors (Fletcher, Mintz, Arakawa and Fox) use a two-level atmospheric general-circulation model with simplified boundary conditions to examine the effects of full ice-cover and no ice-cover at the end of 400-day integrations. The more dramatic changes occur in Eurasia but the authors acknowledge that the results should be treated with reserve. A Russian contribution (Borisenkov and Chernukhin) examines the hemispheric distribution of 'useful potential energy' north of 50°N, and notes in passing the similarity between the variation of annual means of useful potential energy and Wolf numbers (sunspot activity) for the period 1958–68. Another Russian contribution (without offering any evidence) reasons that stratospheric warmings both Arctic and Antarctic are the result of localized meridional processes originating in the troposphere.

In the final section on the interaction between the ocean and the atmosphere there are two papers, one on the ice movement in the Gulf of St Lawrence, and the other on the electromagnetic and optic characteristics of sea-ice, both of which are not really pertinent to the subject of the Symposium.

The question arises whether WMO *Technical Notes* are the correct vehicle for symposium proceedings. In the present volume many of the authors are authorities in their own chosen field, and are stressing particular narrow aspects or

unorthodox points of view. Consequently one does not get an unbiased account, and I would have preferred such a subject to have been treated by a single author in the form of a review paper. Because of the lack of coherent style and the uneven standard of both text and diagrams I cannot recommend this publication as an introduction to a study of polar energy fluxes, but to those meteorologists who are prepared to be selective there are some items worthy of consideration.

D. W. S. LIMBERT

NOTES AND NEWS

Retirement of Mr T. H. Kirk

After graduating in mathematics at King's College, London in 1935 and then taking a Diploma of Education, Mr T. H. Kirk turned to meteorology in 1937, starting his career in the Meteorological Office at Kew. Early in the war he was gazetted Flight Lieutenant in the Royal Air Force Volunteer Reserve and was mentioned in dispatches for his service in France. Later in 1940 he went to Wick and in 1942 he opened an office in the Faeroes. Promotion to Squadron Leader followed and in 1943 he was attached to the Royal Air Force in North Africa and subsequently moved with his Unit to Malta and Italy.

On demobilization Mr Kirk was posted to Harrow where he served as a Senior Scientific Officer in the Marine Branch for three years. This was followed by eight years at London/Heathrow Airport where he was promoted to Principal Scientific Officer in 1949. In 1957 he returned to Malta, where he spent the next six years as officer in charge. His wide experience of Mediterranean forecasting was put to good use in 1961 when he was a principal lecturer at a WMO/ICAO seminar for Middle East forecasters.

Mr Kirk was awarded special merit promotion to Senior Principal Scientific Officer in September 1963, and from then until his retirement on 31 May 1975 he served in the Central Forecasting Office (CFO) at Bracknell as Chief Forecasting Adviser. He became an acknowledged expert on analysis techniques, writing papers on a variety of topics in this field. His extensive knowledge of the use of satellite information and the evaluation of forecasts has been of great value. His quiet presence will be missed in CFO, where he kept a watchful eye on the day-to-day problems and continually sought ways of improving forecasting techniques. In the international field he represented the Office on the WMO Working Group on the Global Data Processing System.

Hubert Kirk's colleagues and friends will wish him a long and happy retirement.

M.H. FREEMAN

The new Meteorological Office Dry Spell Service

Farmers and growers who need to plan their work to make good use of spells of dry weather may wish to take advantage of the new Meteorological Office Dry Spell Service. The service is consultative and puts the farmer in direct touch with a forecaster specializing in regional weather.

Whenever three consecutive days of dry weather are expected subscribers are notified by telephone, or by telex if they prefer. Subsequently they may ring back to discuss with the forecaster any queries which they may have. For example, the messages are concerned only with the likelihood of rain, but if as well as rain-less weather the farmer needs light winds, or drying winds, or sunshine for a particular job he is welcome to contact the forecaster about those conditions. On the other hand, when a dry spell looks like ending, the farmer may want to know more about the kind of weather to be expected. He may find for example that the forecaster expects thunderstorms to break out but is not sure which districts they will affect. The chance that the farmer then decides to take with his operations may depend on the state of his work and the backwardness or otherwise of the season, as well as upon the forecaster's assessment of the weather risks.

Full details of the service may be obtained from:

*The Director-General
Meteorological Office, Met O 7(a)
London Road
Bracknell
Berkshire RG12 2SZ*

OBITUARY

It is with regret that we record the death on 14 February 1975 of Mr R. E. Bywater, Higher Scientific Officer, Meteorological Office, Royal Air Force Lyneham.

CORRECTION

Meteorological Magazine, March 1975, p. 73, Table I. The entry in the column headed 'height of rim above surface' and opposite 'WMO flush' should be 0 cm.

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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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LERWICK ANEMOGRAPH RECORDS 1957-70 AND THE OFFSHORE INDUSTRY

By H. C. SHELLARD

Summary. Hourly mean winds from Lerwick Observatory for the 14 years 1957-70 are analysed to show the frequencies of strong winds of various durations and speeds from different directions. Details of some outstanding storms are given and estimates are made of probable extreme speeds for various averaging periods. The results, modified to represent conditions over the open sea, are used in conjunction with some well-known wave/wind relationships to provide estimates of wave-height frequencies for different direction ranges and of probable extreme wave heights in the Shetland area.

Introduction. Increasing mineral exploration in the northern North Sea in recent years with the discovery of some important oil fields to the east of the Shetland Islands has led to an increased demand from the offshore industry for detailed wind analyses for use in the design and operation of offshore structures. In order to answer such questions as 'how often is a wind of 40 kt or more likely to blow for 12 hours or more from a given direction?' or 'what is the wind speed averaged over 6 hours that is likely to be exceeded only once in 50 years?', it is essential to have a long series of continuous wind records in computer-accessible form. Such observational material is simply non-existent for the offshore sea areas, nor can it possibly be made available for at least another 10 years, by which time the need for it will probably have become less urgent.

However, we already have long-period continuous wind records for Lerwick Observatory and the data for the 14 years 1957-70 are available on magnetic tape. These data can be analysed to answer the sorts of question mentioned above and the results used to provide good estimates of wind conditions over the open sea in the general vicinity of the Shetland Islands, together with an indication of the wave conditions that they are likely to generate. Attention will be mainly confined to wind speeds averaging 25 kt or more and to durations of between 1 hour and 24 hours.

Frequencies of storms of various durations. Table I gives for each of the 12 30-degree direction ranges (350-010°, 020-040°, - - - - 320-340°) the numbers of spells of various durations during which successive hourly mean speeds were 25 kt or more, 30 kt or more and so on. The first part (350-010°) shows, for example, that there were six occasions during the 14 years when for

spells of 9 to 11 hours all hourly mean speeds were 30 kt or more from a direction in the range 350–010°. It should be noted that the frequencies are non-cumulative with respect to duration, i.e. a spell of, say, 12 hours with speeds of 30 kt or more is counted only once, in the column headed 12–14 hours, and is not also counted as two six-hour spells, four three-hour spells and so on. Hence, addition of the number in column 1, three times the number in column 2, six times the number in column 3, and so on, will approximately give the total number of hours with speeds equal to or greater than the speed concerned. However, exact total hours are given in the final column of each table. Incidentally, if these values are divided by the total numbers of spells given in the previous column, average spell-lengths for each speed level and direction are obtained and it is of some interest that these tended to be longest for wind directions from between 110 and 190° and to decrease in length with increasing speed.

An important conclusion from Table I is that the most severe storms (mean speeds of 55 kt or more throughout) came from directions between 200 and 280°. However, if attention is confined to storms having durations of three hours or more and mean speeds of 40 kt or more, that is to say, to storms which are likely to produce significant wave heights of over 5 metres, assuming that fetches are not limiting, their distribution with wind direction was as follows:

Direction range	Number of storms	Direction range	Number of storms
350–010°	3	170–190°	7
020–040°	3	200–220°	6
050–070°	0	230–250°	21
080–100°	0	260–280°	13
110–130°	0	290–310°	3
140–160°	6	320–340°	2
		Total	64

Clearly, storms which are of sufficient intensity and duration to produce high waves may come from a wide range of directions in the Shetland area. However, more than half of them came from between 230 and 280°, while directions between 050 and 130° produced none and so seem unlikely to develop very big seas. The anemograph at Lerwick has a good open exposure in all directions. The only shelter from easterly winds is provided by the small island of Bressay, bearing about 030 to 110°, rising to a height of about 225 m at a distance of about 5½ km. Its effect is not likely to be very great as its terrain is relatively smooth and treeless.

In the original computer tabulations, frequencies were included for every duration, at 1-hour intervals, from 1 to 35 hours and for the ranges 36–41, 42–47, 48–59, 60–71 and 72 hours or more. They were given separately for the periods April to September and October to March as well as for the year as a whole. To give an indication of the seasonal variation the total frequencies for all directions are given in Table II for 'summer' (April–Sept.), 'winter' (Oct.–March) and for the whole year. Although the winter half-year accounts for a large majority of the storms, over 70 per cent in most categories, the summer half-year does experience an appreciable number with mean speeds of 40 kt or more lasting for several hours. However, every one of the 13 storms with mean speeds of 45 kt or more throughout, which occurred in the summer half-year took place either in

April or in September, there being none at all during the months May to August over the 14-year period. This is shown in Table III which gives the monthly distributions of the number of hours with mean speeds of 25, 30, 35, 40, 45, 50, 55 and 60 kt or more, irrespective of direction. It may also be seen that over the 14 years there were only 14 hours, one per year on the average, having mean speeds of 40 kt or more during the four months May to August, compared with 491 such hours in the other eight months of the year.

TABLE I—FREQUENCY OF SPELLS OF DURATIONS FROM 1 HOUR TO 24 HOURS OR MORE WITH HOURLY MEAN WIND SPEEDS EQUAL TO OR GREATER THAN THE STATED VALUES AND WITH MEAN WIND DIRECTIONS WITHIN THE STATED 30-DEGREE RANGES AT LERWICK (NUMBERS OF OCCURRENCES IN THE 14 YEARS 1957-70)

Speed (kt) ≥	Duration (hours)								Totals Spells Hours	
	1,2	3-5	6-8	9-11	12-14	15-17	18-23	≥ 24		
	Numbers of occurrences								Spells	Hours
	350-010°									
25	129	53	16	11	5	1	3	1	219	753
30	55	20	6	6	1			1	89	282
35	14	7	2					1	24	82
40	7	2					1		10	34
45	1			1					2	11
50	2	1							3	6
020-040°										
25	105	51	17	9	3	4	2	1	192	697
30	53	22	7	1	2	2	1		88	283
35	29	13	1	1					44	106
40	12	3							15	23
45	2								2	2
050-070°										
25	41	14	13	1	4			1	74	288
30	17	13	6					1	37	135
35	9	4	2		1				16	51
40	7								7	10
45	1								1	1
080-100°										
25	35	15	6	2	3	2	1		64	262
30	16	8	1	1	1		1		28	105
35	4	2				1			7	31
40	2								2	2
110-130°										
25	76	34	17	7	6	1	2	6	149	743
30	40	25	5	3	2	1	1		77	273
35	9	1	1		1				12	38
40	2								2	4
140-160°										
25	142	74	25	13	7	3	4	15	283	1489
30	59	32	12	6	4	3	3	4	123	640
35	19	10	5		1	1	3		39	185
40	7	6							13	32
45	3								3	3
170-190°										
25	149	76	35	26	10	9	8	6	319	1643
30	73	41	21	12	5	1	4	1	158	720
35	28	13	9	3					53	180
40	8	2	4	1					15	54
45	4	2	1						7	19

ranging from 6 hours (number 7) to 37 hours (number 6). If the threshold speed had been set at only 25 kt the durations would have averaged about 25 hours, ranging from 15 hours (number 1) to 54 hours (number 2). It can be seen that if the threshold speed had been 40 kt then durations would have ranged from only 2 hours (number 13) to 21 hours (number 6). In some of the storms the maximum speed was reached in a few hours, for example in numbers 7, 10 and 13, but in others much more slowly, for example numbers 3 and 6. The rates of decline were also very variable. In only one of the 15 storms (number 6) did the wind direction back with time; in all the others it veered, sometimes gradually, sometimes more sharply. The total direction change, for a 30-knot threshold speed, ranged from about 20 degrees to about 100 degrees.

There is an apparent discrepancy between the 15 storms of Figure 1 and the 20 spells with hourly mean speeds of 50 kt or more shown by Table II. The explanation lies in the fact that some of the storms of Figure 1 include more than one of the spells listed in Table II, which represent all occasions of one hour or more with speeds of 50 kt or more from within one of the 12 fixed 30-degree direction ranges. Thus storm number 3 (Figure 1) includes a one-hour spell from 200–220° and a two-hour spell from 230–250° while storm number 6 includes one three-hour and one two-hour spell, each from 350–010° but separated by an hour with mean speed below 50 kt.

The storms whose profiles are shown in Figure 1 were selected on the basis of a high maximum speed, irrespective of wind direction. Some of these may not

TABLE II—FREQUENCIES OF SPELLS OF DURATIONS FROM 1 HOUR TO 24 HOURS OR MORE WITH HOURLY MEAN WIND SPEEDS EQUAL TO OR GREATER THAN THE STATED VALUES AND FOR ALL DIRECTION RANGES COMBINED AT LERWICK (NUMBERS OF OCCURRENCES IN THE 14 YEARS 1957-70 FOR SUMMER (APRIL-SEPTEMBER), WINTER (OCTOBER-MARCH) AND YEAR)

[illegible]

TABLE III—TOTAL NUMBERS OF HOURS WITH MEAN WIND SPEEDS EQUAL TO OR GREATER THAN STATED VALUES IN EACH MONTH DURING THE 14 YEARS 1957–70 AT LERWICK, IRRESPECTIVE OF DIRECTION

	Mean speed equal to or greater than							
	25 kt	30 kt	35 kt	40 kt	45 kt	50 kt	55 kt	60 kt
	<i>Numbers of hours</i>							
January	1 981	919	317	109	26	8	5	4
February	1 464	642	201	89	29	5	2	
March	1 998	949	210	40	8	3		
April	799	295	89	25	7	2	1	
May	445	173	46	10				
June	584	154	7					
July	259	41	11					
August	265	71	20	4				
September	640	263	87	45	20	10	3	
October	1 309	522	184	66	22	9	2	
November	1 302	422	120	29	2			
December	1 965	976	386	88	9	2		
Year	13 011	5427	1678	505	123	39	13	4

have been very effective in generating high waves either because the higher speeds were of limited duration or because there were marked changes in wind direction. An alternative selection of notable storms could be made on the basis of a high average speed over a longer period, say 40 kt or more over 12 hours, combined with a limited direction range, say 40 degrees or less. There were 13 storms which met these criteria, seven of which already appear in Figure 1 (numbers 2, 3, 6, 8, 10, 11 and 12) and the other six of which are shown in Figure 2. In both figures a horizontal line drawn beneath each relevant speed profile shows the 12-hour period giving the highest average speed, and is labelled to show the average speed and direction range concerned.

Like the 15 storms of Figure 1, these 13 12-hour storms have no common feature, although the majority of the speed profiles show an increase followed by a decrease, and the majority of the direction profiles show a more or less steady veer with time. Thus it cannot be said that there is a typical storm profile.

Extreme wind speeds. Table IV shows the highest mean wind speeds, reduced to the standard height of 10 m, recorded in each of the years 1957 to 1970 for durations ranging from 1 hour to 72 hours and for direction ranges of 40 degrees or less. In any one year the highest speeds are given for each duration irrespective of the storm in which they occurred, but as the times and dates of commencement are given it can easily be seen which spells occurred in the same storm. Out of the 14 years there were 9 in which hourly mean speeds of 50 kt or more occurred, the highest speed being 63 kt in January 1961. Nine years also produced 6-hour mean speeds of 45 kt or more, seven years gave 12-hour means of 40 kt or more while 11 years gave 24-hour means of 35 kt or more. Even over as long a period as 48 hours, eight of the 14 years gave mean speeds of 30 kt or more.

Tables V and VI give the annual extreme speeds over 12-hour and 24-hour periods respectively, together with the highest speeds averaged over shorter periods in the same storms. As in Table IV the speeds were reduced to the standard height of 10 m and are for direction ranges of 40 degrees or less.

TABLE IV—HIGHEST MEAN WIND SPEEDS IN KNOTS OVER STATED DURATIONS IN EACH OF THE YEARS 1957 TO 1970 AT LERWICK, WITH TIMES OF COMMENCEMENT (GMT); DIRECTION RANGES ARE RESTRICTED TO 40° FOR DURATIONS OF 3 HOURS OR MORE, AND SPEEDS ARE REDUCED TO THE VALUES APPROPRIATE TO A HEIGHT OF 10 METRES

	Duration (hours)									
	1	3	6	12	18	24	36	48	72	
1957	54 11h 5 Feb	51·9 11h 5 Feb	49·2 11h 5 Feb	44·0 11h 5 Feb	36·9 19h 19 Jan	36·7 22h 7 Jan	35·3 13h 7 Jan	27·6 12h 13 Sept	20·6 4h 17 Nov	
1958	52 18h 18 Jan	46·5 17h 18 Jan	40·3 2h 29 Dec	39·4 1h 29 Dec	37·5 21h 28 Dec	35·9 21h 28 Dec	33·1 8h 12 Dec	30·0 13h 28 Dec	23·9 19h 25 Jan	
1959	49 4h 28 Oct	49·3 23h 27 Oct	49·1 23h 27 Oct	46·5 20h 27 Oct	44·8 13h 27 Oct	43·4 9h 27 Oct	40·3 8h 27 Oct	36·7 8h 6 Dec	29·9 17h 9 Mar	
1960	50 4h 14 Apr	46·6 3h 14 Apr	40·6 6h 5 Apr	38·9 oh 5 Apr	37·9 18h 4 Apr	37·0 13h 4 Apr	35·0 1h 4 Apr	32·4 17h 19 Mar	31·2 21h 18 Mar	
1961	63 20h 27 Jan	62·7 18h 27 Jan	49·1 13h 27 Jan	42·9 7h 27 Jan	39·8 1h 27 Jan	41·0 19h 26 Jan	38·6 7h 26 Jan	30·0 18h 17 Jan	27·4 oh 17 Jan	
1962	44 3h 16 Feb	44·0 21h 11 Jan	42·2 oh 16 Feb	39·3 19h 15 Feb	36·1 16h 15 Feb	33·5 10h 15 Feb	29·4 7h 9 Jan	21·8 5h 29 Jan	18·6 10h 23 May	
1963	58 17h 26 Sept	56·0 16h 26 Sept	54·5 15h 26 Sept	46·8 14h 26 Sept	37·2 21h 24 Dec	36·6 15h 24 Dec	36·8 3h 24 Dec	30·7 18h 22 Dec	23·8 18h 26 Jun	
1964	47 11h 12 Dec	45·3 10h 12 Dec	42·8 10h 12 Dec	39·7 13h 14 Mar	38·7 10h 14 Mar	37·7 9h 14 Mar	36·3 23h 13 Mar	35·4 13h 13 Mar	33·0 2h 13 Mar	
1965	58 20h 28 Oct	55·0 19h 28 Oct	52·2 17h 28 Oct	46·8 14h 28 Oct	36·3 22h 30 Oct	32·8 18h 30 Oct	27·1 5h 13 Feb	24·1 5h 13 Feb	22·6 17h 7 Apr	
1966	52 16h 23 Dec	47·7 13h 6 Sept	47·0 13h 6 Sept	44·8 11h 6 Sept	38·2 15h 6 Sept	36·0 15h 6 Sept	32·1 15h 6 Sept	29·8 15h 6 Sept	24·4 5h 8 Jan	
1967	53 15h 6 Mar	51·7 14h 6 Mar	48·8 12h 6 Mar	39·5 4h 3 Dec	37·4 9h 21 Mar	35·6 5h 21 Mar	31·8 oh 21 Mar	30·8 10h 20 Mar	27·3 1h 15 Feb	
1968	47 13h 4 Feb	47·0 11h 4 Feb	46·2 10h 4 Feb	44·7 8h 4 Feb	42·3 5h 4 Feb	37·7 3h 4 Feb	31·0 13h 2 Apr	27·1 12h 30 Oct	25·7 16h 12 Nov	
1969	50 23h 28 Sept	48·7 22h 28 Sept	45·5 21h 28 Sept	39·1 21h 28 Sept	37·9 8h 14 Dec	37·1 2h 14 Dec	35·6 16h 13 Dec	34·4 11h 13 Dec	30·6 19h 14 Mar	
1970	42 1h 24 Apr	41·3 oh 24 Apr	40·5 22h 23 Apr	37·8 21h 23 Apr	35·2 20h 23 Apr	32·7 19h 23 Apr	28·9 5h 19 Oct	27·4 2h 21 Jan	24·9 2h 21 Jan	
All years	63 27/1/61	62·7 18h 27/1/61	54·5 15h 26/9/63	46·8 14h 26/9/63	44·8 13h 27/10/59	43·4 9h 27/10/59	40·3 8h 27/10/59	36·7 8h 6/12/59	33·0 2h 13/3/64	

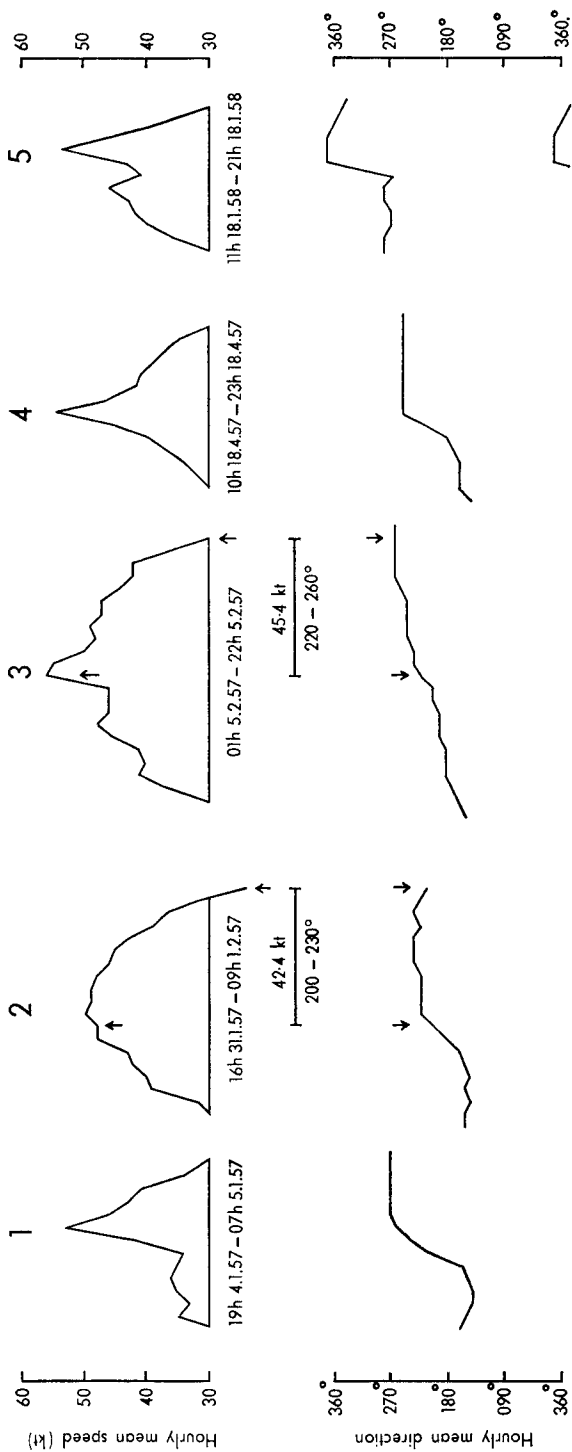


FIGURE 1—PROFILES OF 15 STORMS IN WHICH AN HOURLY MEAN SPEED OF 50 KNOTS OR MORE WAS RECORDED AT LERWICK DURING THE PERIOD 1957-70 INCLUSIVE

Storms numbered 2 and 3 include 12-hour periods with average speeds of 40 kt or more and direction ranges of 40° or less.

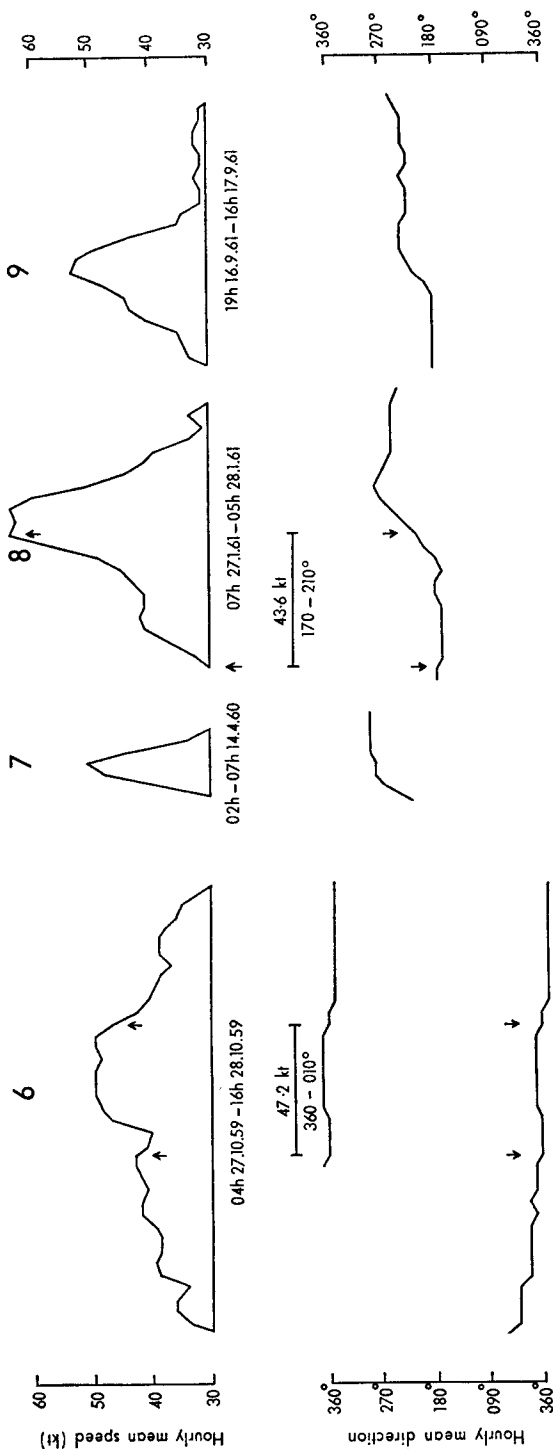


FIGURE 1—continued
Storms numbered 6 and 8 include 12-hour periods with average speeds of 40 kt or more and direction ranges of 40° or less.

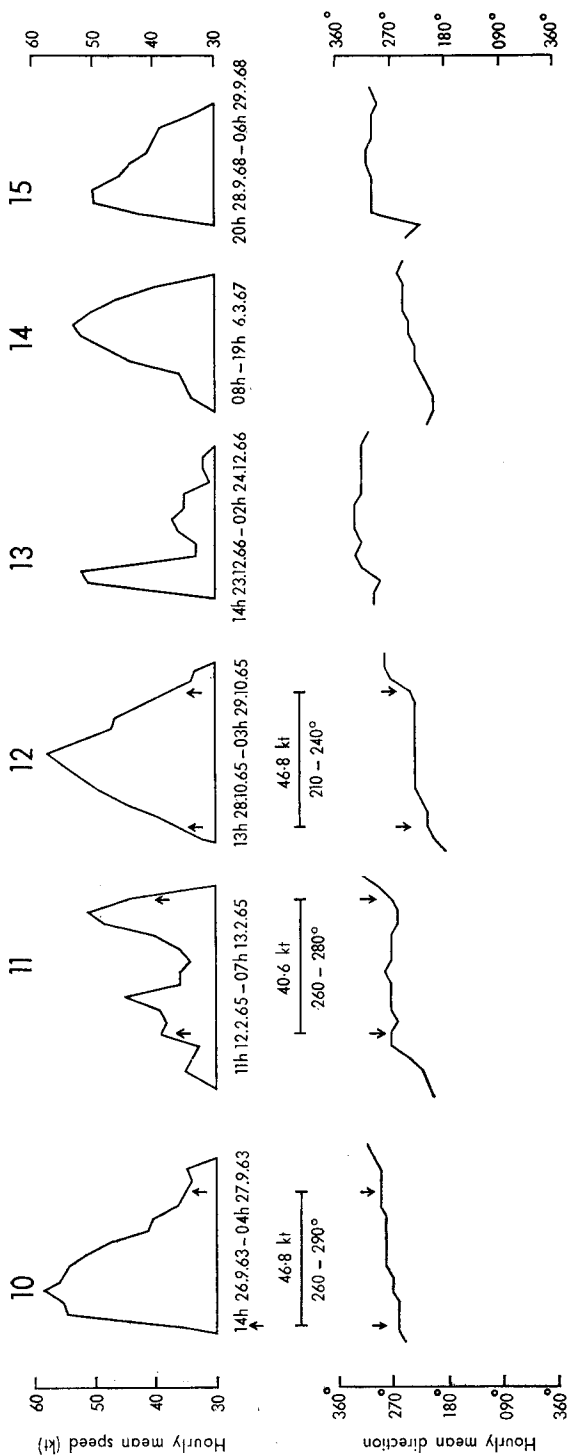


FIGURE 1—continued
Storms numbered 10, 11 and 12 include 12-hour periods with average speeds of 40 kt or more and direction ranges of 40° or less.

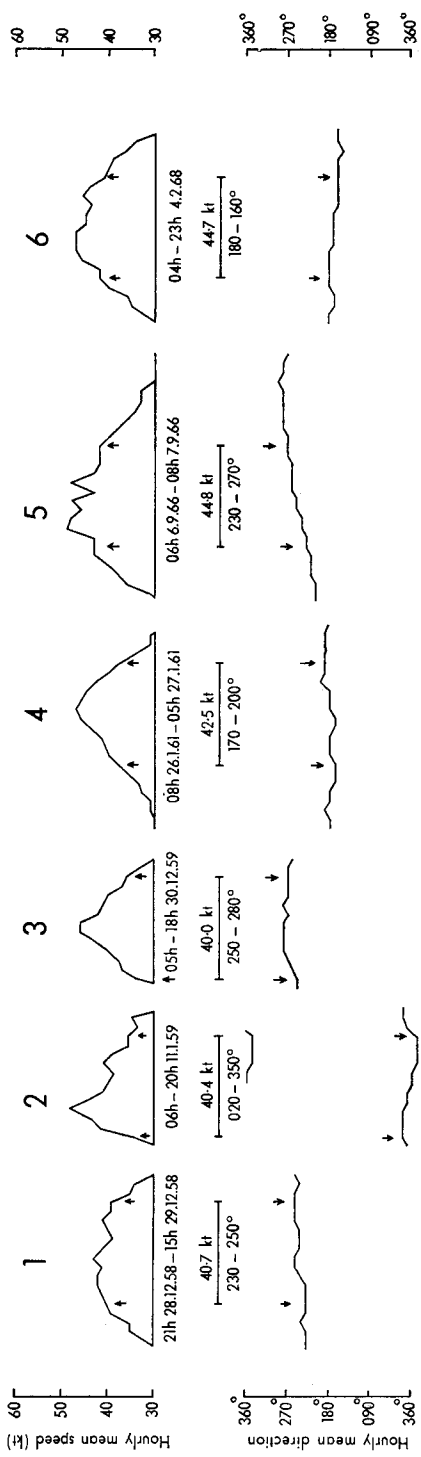


FIGURE 2—PROFILES OF SIX ADDITIONAL STORMS IN WHICH THERE WERE 12-HOUR PERIODS WITH AVERAGE SPEEDS OF 40 KNOTS OR MORE AND DIRECTION RANGES OF 40 DEGREES OR LESS AT LERWICK DURING THE PERIOD 1957-70 INCLUSIVE

TABLE V—HIGHEST MEAN WIND SPEED IN KNOTS OVER A 12-HOUR PERIOD DURING WHICH THE DIRECTION RANGE DID NOT EXCEED 40° IN EACH OF THE YEARS 1957 TO 1970 AT LERWICK, TOGETHER WITH MAXIMUM SPEEDS OVER PERIODS OF 1 HOUR AND 3, 6, AND 9 HOURS IN THE SAME STORMS; ALL SPEEDS ARE REDUCED TO VALUES APPROPRIATE TO A HEIGHT OF 10 METRES

	Duration (hours)					Times of commencement
	1	3	6	9	12	
	<i>knots</i>					
1957	54	51·9	49·2	47·1	44·0	11h 5 Feb.
1958	42	40·6	40·3	39·8	39·4	1h 29 Dec.
1959	49	49·3	49·1	48·4	46·5	20h 27 Oct.
1960	44	42·4	40·6	39·5	38·9	0h 5 Apr.
1961	63	55·8	49·1	46·3	42·9	7h 27 Jan.
1962	44	43·3	42·2	40·8	39·3	19h 15 Feb.
1963	58	56·0	54·5	50·6	46·8	14h 26 Sept.
1964	42	41·3	40·7	40·2	39·7	12h 14 Mar.
1965	58	55·0	52·2	49·7	46·8	14h 28 Oct.
1966	49	47·7	47·0	45·7	44·8	11h 6 Sept.
1967	42	41·0	40·7	40·1	39·5	4h 3 Dec.
1968	47	47·0	46·2	45·7	44·7	8h 4 Feb.
1969	50	48·7	45·5	42·9	39·1	21h 28 Sept.
1970	42	41·3	40·5	39·1	37·8	21h 23 Apr.

TABLE VI—HIGHEST MEAN WIND SPEED IN KNOTS OVER A 24-HOUR PERIOD DURING WHICH THE DIRECTION RANGE DID NOT EXCEED 40° IN EACH OF THE YEARS 1957 TO 1970 AT LERWICK, TOGETHER WITH MAXIMUM SPEEDS OVER PERIODS OF 1 HOUR AND 3, 6, 9, 12, 15 AND 18 HOURS IN THE SAME STORM; ALL SPEEDS ARE REDUCED TO VALUES APPROPRIATE TO A HEIGHT OF 10 METRES

	Duration (hours)								Times of commencement
	1	3	6	9	12	15	18	24	
	<i>knots</i>								
1957	41	39·4	38·6	38·5	38·1	37·0	36·3	36·7	20h 7 Jan.
1958	42	40·6	40·3	39·8	39·4	38·5	37·5	35·9	21h 28 Dec.
1959	49	49·3	49·1	48·4	46·5	45·6	44·8	43·4	9h 27 Oct.
1960	44	42·4	40·6	39·5	38·9	38·2	37·9	37·0	13h 4 Apr.
1961	63	55·8	49·1	46·3	42·9	40·3	39·8	41·0	19h 26 Jan.
1962	44	43·3	42·2	40·8	39·3	37·9	36·1	33·5	10h 15 Feb.
1963	46	45·0	43·0	41·2	39·8	38·3	37·2	36·6	15h 24 Dec.
1964	42	41·3	40·7	40·2	39·7	39·2	38·7	37·7	9h 14 Mar.
1965	47	44·3	41·5	40·6	38·8	37·5	36·3	32·8	18h 30 Oct.
1966	48	46·3	45·0	43·8	41·8	39·9	38·2	36·0	15h 6 Sept.
1967	47	45·0	42·5	40·9	39·1	37·7	37·4	35·6	5h 21 Mar.
1968	47	47·0	46·2	45·7	44·7	43·7	42·3	37·7	3h 4 Feb.
1969	40	39·3	39·0	38·9	38·6	38·3	37·9	37·1	2h 14 Dec.
1970	42	41·3	40·5	39·1	37·8	36·9	35·2	32·7	19h 23 Apr.

Amongst other things the data in Tables IV, V and VI may be used to estimate how extreme wind speeds fall off as the averaging period is increased beyond one hour. Average speeds over the 14 years for each duration were computed from each table and expressed as ratios of the averages over one hour, and the results are given in Table VII. As was to be expected, the mean ratios derived from the same storms for each year, that is to say from Tables V and VI,

are somewhat higher than those based on the highest speeds irrespective of the storms in which they occurred, as given in Table IV, particularly for the longer averaging periods. It is suggested that the ratios in line (a) of Table VII should be used when, given an extreme hourly mean speed such as might be computed from anemograph records or interpolated from a map of once-in-50-year hourly mean speeds, it is desired to estimate an extreme for a longer period, say 24 hours, having the same probability, it being understood of course that the longer period is one in which wind direction remains within a 40-degree range. Thus if the once-in-50-year hourly mean speed was 65 kt then the estimated once-in-50-year 12-hour and 24-hour means would be about $65 \times 0.82 = 53$ kt and $65 \times 0.71 = 46$ kt respectively. The ratios on lines (b) and (c) of Table VII on the other hand might be used when, given an extreme for one averaging period, it was desired to estimate probable extremes for other, longer or shorter, averaging periods in the same storm. Thus, given a highest 24-hour mean of 45 kt in a storm with no great direction change the probable highest 3-hour mean in the same storm would be about $45 \times 0.97/0.80 = 55$ kt; or given a highest hourly mean of 60 kt the probable 12-hour extreme in the same storm, assuming no great direction change, would be about $60 \times 0.86 = 52$ kt. Also shown on line (d) of Table VII are ratios previously estimated by Shellard and published by the Department of Energy,¹ which are in very good agreement with those now derived from 24-hour storms at Lerwick.

TABLE VII—RATIOS OF MAXIMUM SPEEDS AVERAGED OVER VARYING NUMBERS OF HOURS (V_t) TO MAXIMUM SPEEDS OVER ONE HOUR (V_1) AT LERWICK

	Period t (hours)						
	3	6	12	18	24	36	48
			Ratio V_t/V_1				72
(a)	0.96	0.90	0.82	0.74	0.71	0.66	0.51
(b)	0.97	0.93	0.86				
(c)	0.97	0.93	0.88	0.83	0.80		
(d)	0.96	0.93	0.87		0.80		

- (a) derived from annual extremes for each duration irrespective of the storm in which they occurred;
- (b) from maximum 12-hour storms;
- (c) from maximum 24-hour storms;
- (d) for comparison—values as given by Shellard in reference 1.

The annual extreme wind speeds presented in Tables IV, V and VI may be fitted by extreme-value distributions of the Gumbel type, so providing estimates of extreme wind speeds for different averaging periods (durations) likely to be exceeded on average only once in, say, 50 or 100 years. Such estimates have been computed for average recurrence periods of 10, 20, 50, 100 and 200 years and are presented in Table VIII. Those in part (a) of the table were derived from Table IV and once-in-50-year extremes range from 71 kt for hourly means to 40 kt for 72-hour means. Those in parts (b) and (c) were derived from Tables V and VI and give for the same recurrence periods the probable extreme speeds in 12-hour and 24-hour storms respectively. In all cases direction ranges are assumed to be 40 degrees or less.

TABLE VIII—ESTIMATED EXTREME WIND SPEEDS AT LERWICK FOR VARIOUS DURATIONS AND AVERAGE RECURRENCE PERIODS

(a) Estimated from data in Table IV, i.e. from highest speeds irrespective of the storms in which they occurred.

Average recurrence period	Duration (hours)								
	1	3	6	12	18	24	36	48	72
	<i>Extreme wind speed in knots for durations shown</i>								
10 years	61	59	54	48	43	42	40	37	33
20 years	65	63	57	50	45	44	43	40	36
50 years	71	68	61	53	47	46	47	44	40
100 years	75	72	65	56	49	48	49	47	43
200 years	79	76	68	58	50	50	52	49	46

(b) Estimated from data in Table V, i.e. from highest speeds in maximum 12-hour storms.

Average recurrence period	Duration (hours)				
	1	3	6	9	12
	<i>Extreme wind speed in knots for durations shown</i>				
10 years	61	57	54	51	48
20 years	66	61	57	54	50
50 years	72	67	62	58	53
100 years	77	71	65	61	56
200 years	82	75	68	63	58

(c) Estimated from data in Table VI, i.e. from highest speeds in maximum 24-hour storms.

Average recurrence period	Duration (hours)							
	1	3	6	9	12	15	18	24
	<i>Extreme wind speed in knots for durations shown</i>							
10 years	56	52	49	47	45	44	43	42
20 years	60	55	51	49	47	45	45	44
50 years	65	59	54	52	49	48	47	46
100 years	69	62	57	54	51	49	49	48
200 years	73	65	59	56	53	51	51	50

Application to wave prediction. As mentioned earlier, the original computer tabulations gave for each 30-degree direction range the numbers of spells with speeds equal to or greater than 20, 25, 30 etc. kt, and with durations of 1, 2, 3, . . . 35 hours and 36 hours or more. By employing the wave-prediction technique of Darbyshire and Draper,² modified by Draper,³ these frequencies may be converted into wave-height frequencies. The relationship is not a simple one since wave height depends on both wind speed and duration, but the procedure used is illustrated in Table IX. In this table the numbers of 3-hour spells with speeds exceeding the values in column 1 and with directions in the range 230–250° is given in column 2. In column 3 the speeds of column 1 were adjusted to represent more closely the probable mean speeds over the open sea rather than those measured at Lerwick itself. The correction applied was a straightforward increase of 10 per cent, which figure was arrived at as follows. At coastal anemograph stations and in strong winds the average ratio of the

maximum gust speed to the maximum hourly mean speed, G (3-s, 60-min) has been shown by Shellard⁴ to be about 1.5. Measurements over the sea by Goptarev,⁵ Dorrestein⁶ and Walden⁷ suggest that G (3-s, 10-min) is no more than 1.3 and this corresponds to a value of G (3-s, 60-min) of about 1.37. Also recent measurements on fixed gas-production platforms in the southern North Sea have shown G (3-s, 60-min) to be about 1.2 for anemographs at a height of 80 m or so. When speeds are reduced to the standard height of 10 m using appropriate power-law formulae (exponent 0.12 for hourly means and 0.06 for gusts) this too gives a ratio of about 1.37. On the assumption that in strong winds maximum gust speeds will be much the same over the open sea as they are on nearby coasts, both being mainly dependent on the gradient wind speed, maximum hourly mean speeds over the sea will be about 1.50/1.37 or about 1.10 times those on nearby coasts.

Next it was necessary to decide which set of wave-prediction graphs provided by Darbyshire and Draper should be used, those for oceanic waters or those for coastal waters. On the advice of one of the authors (L. Draper, personal communication) the oceanic-waters graphs were used as being more appropriate to the Shetland area. It should be mentioned that the oceanic-waters graphs were derived from measurements made at the ocean weather stations 'I' and 'J', that is to say from wind speeds measured over the open sea. Had the coastal-waters graphs been used it would have been more correct to use the wind speeds as measured at Lerwick because these graphs were based on wind measurements made at coastal stations. The wave-prediction graphs provide estimates of (a) maximum wave height in feet during a 10-minute period and (b) significant wave period in seconds, for various combinations of wind speed and duration (or fetch). The appropriate values of these items are given in columns 4 and 5 of Table IX, wave heights being converted to metres. Columns 6 and 7 give the numbers of waves in the storm (in this case in three hours) and in the 10-minute period respectively, and column 8 gives the corresponding wave-height factors F_2 and F_1 , obtained from a diagram given by Draper (Figure 2 of reference 3) and their ratio. This diagram gives the ratio of maximum wave height to root-mean-square wave height for various numbers of waves. Since this ratio increases with number of waves, the ratio F_2/F_1 represents the greater chance of a number of component waves getting into phase during the whole storm than in the 10-minute recording period on which the wave-prediction graphs are based; thus the last column of Table IX gives values of H_{\max} (10-min) $\times F_2/F_1$, the estimated maximum wave height in the storm.

Hence, from each set of wind-speed frequencies, one for each direction range and duration, a set of highest-wave-in-storm frequencies can be obtained. These frequencies, derived from storms of various durations, can then be combined to give overall frequencies of waves exceeding various heights from each direction. This was done by plotting each set of frequencies against wave heights, for example column 2 against column 9 of Table IX, on log-linear graph paper and then reading off, by interpolation, the frequencies of wave heights at intervals of $1\frac{1}{2}$ metres from $4\frac{1}{2}$ metres upwards. These were then summed to give the results presented in Table X.

In the process of deriving Table X some information was obtained which related highest storm waves to storm duration. This is summarized in Table XI which gives numbers of storms in which the predicted highest wave exceeded stated heights, arranged according to storm duration, all wind directions being

TABLE IX—EXAMPLE OF THE APPLICATION OF THE DARBYSHIRE—DRAPER WAVE-PREDICTION TECHNIQUE TO THE 3-HOUR STORM FREQUENCIES FOR THE 230–250° DIRECTION RANGE AT LERWICK, 1957–70

Mean wind speed equal to or greater than <i>kt</i>	Number of 3-hour storms from 230–250°	Estimated wind speed over open sea equal to or greater than <i>kt</i>	Maximum wave height <i>H</i> _{max} (10-min) equal to or greater than <i>m</i>	Significant wave period <i>s</i>	Number of waves in storm	Number of waves in 10 minutes	Ratio of wave-height factors* <i>F</i> ₂ / <i>F</i> ₁	Highest wave in storm equal to or greater than <i>m</i>
20	127	22	1.4	5.8	1860	103	1.28	1.8
25	87	27.5	2.7	6.8	1590	88	1.28	3.5
30	57	33	4.0	8.2	1320	73	1.29	5.2
35	17	38.5	5.8	9.1	1190	66	1.29	7.5
40	8	44	8.1	10.3	1050	58	1.29	11.3
45	1	49.5	10.5	11.4	950	53	1.30	13.6
50	1	55	13.4	12.8	840	47	1.31	17.5

* See page 203 for explanation of these factors.

TABLE X—NUMBERS OF STORMS IN 14 YEARS (1957–70) OVER THE SHETLAND ISLANDS IN WHICH THE HEIGHT OF THE PREDICTED HIGHEST WAVE WAS 4½ METRES OR MORE, ARRANGED ACCORDING TO WAVE HEIGHT AND WIND DIRECTION

Wave height <i>metres</i>	Direction range (degrees)													Totals
	350-010	020-040	050-070	080-100	110-130	140-160	170-190	200-220	230-250	260-280	290-310	320-340		
4½ or more	95	94	37	28	87	151	191	239	372	206	82	79	1661	
6 or more	48	46	23	14	45	84	119	130	195	124	45	41	914	
7½ or more	27	27	13	6	17	51	68	60	115	80	24	20	508	
9 or more	14	14	6	2	5	30	35	24	67	48	12	7	264	
10½ or more	8	5	1		2	15	17	12	38	29	6	3	136	
12 or more	6	1				8	10	6	21	14	3	1	70	
13½ or more	4					1	7	5	12	7	3	1	40	
15 or more	3						2	2	8	3			18	
16½ or more	2						1	1	7	3			14	
18 or more	1								2	2			5	
19½ or more									1	1			3	
21 or more									1	2			3	
22½ or more										1			1	

combined. It will be seen that all but one of the 18 storms in which the predicted highest wave was 15 m or more in height had durations of less than 10 hours, that all five storms in which the predicted highest wave was 18 m or more in height had durations of less than 10 hours and that all three storms in which the predicted highest wave was 21 m or more in height had durations of between 2 and 6 hours. It appears that in the Shetland area the highest waves tend to be associated with rather severe gales of relatively short duration. Over the 14-year period there were only two storms having a duration of 24 hours or more and giving predicted highest waves of $10\frac{1}{2}$ m or more and only one storm of duration 36 hours or more giving a predicted highest wave of 9 m or more.

It should be noted that the predicted wave heights given in Tables X and XI take no account of swell. However, according to an analysis of wave data for ocean weather station 'I' (59°N, 19°W) by Hogben⁸ the mean underlying swell in that area of the North Atlantic has a height of about 2 metres. The addition of an average swell wave of 2 m to wind waves of 6 m, 12 m and 24 m would give resultant waves of only 6·3, 12·2 and 24·1 m respectively. Even an exceptionally heavy swell of, say, 6 m when combined with sea waves of 12 and 24 m would give resultant waves of only 13·4 and 24·7 m respectively.

Returning to Table X, it should be stressed that too much significance should not be attached to the actual frequencies given there, or in Table I, bearing in mind how they were obtained. Each 30-degree range was treated separately so that if, in a given storm, the wind direction veered or backed into an adjacent sector, that particular storm would have been terminated, even though the overall direction range may have been small enough for the storm to have been quite effective in developing waves. Also, the greater the duration of a storm the more likely would it be to be terminated in this way, thus being counted as two, or more, storms of lesser duration. However, the relative significance of the frequencies as given will not have been much affected by these occasional happenings and it is thought that the relative frequencies of waves of different heights from various directions are adequately represented by Table X.

The table shows that the three highest waves, those of 21 m or more in height, came from directions between 230 and 280°, whereas those of 15 m or more, averaging just over one per year, came either from between 170 and 280° or from 350–010°. Between the directions 050° and 130° waves of 12 m or more in height appear to be unlikely in the Shetland area.

Probable extreme wave heights. Finally, the Darbyshire/Draper wave-prediction technique may be applied to the extreme-wind-speed estimates given in Table VIII to provide estimates of the highest waves to be expected on average only once in 10, 20, 50, 100 or 200 years. This has been done for an average recurrence period of 50 years using the appropriate wind speeds taken from part (a) of Table VIII and the results are given in Table XII. The values of H_{\max} (10-min) and of wave period enclosed in brackets are values whose derivation necessitated some limited extrapolation of the Darbyshire and Draper graphs. Since some preliminary calculations indicated that the predicted extreme wave heights increased rather quickly to a maximum value as the storm duration increased, interpolated extreme wind speeds for durations of 2, 4 and 5 hours were also used and the results are included in the table in view of the fact that the maximum value and the duration at which it occurs are of special interest.

TABLE XII—PREDICTED EXTREME WAVE HEIGHTS FOR STORMS HAVING AN AVERAGE RECURRENCE PERIOD OF 50 YEARS AND DIFFERENT DURATIONS IN THE SHETLAND AREA

Storm duration hours	Once in- 50-year wind speed kt	Estimated wind speed over open sea kt	Maximum wave height H_{\max} (10-min)	Significant wave period s	Number of waves in storm	Number of waves in 10 minutes	Ratio of wave- height factors F_2/F_1	Highest wave in storm m
1	71	78	(17)	(15½)	232	39	1.20	20½
2	70	77	(24½)	(18½)	389	32½	1.28	31½
3	68	75	(26½)	(19½)	554	31	1.33	35
4	65½	72	(26)	(19)	758	31½	1.36	35½
5	63½	70	25½	18½	964	32	1.38	35
6	61	67	24	18	1 200	33	1.40	33½
12	53	58½	19½	15½	2 787	39	1.45	28
18	47	51½	14½	13½	4 800	44	1.47	21½
24	46	50½	14½	13½	6 400	44	1.51	22
36	47	51½	(15)	(14)	9 257	43	1.53	23
48	44	48½	(13½)	(13)	13 292	46	1.55	21
72	40	44	(11½)	(12½)	20 736	48	1.58	18

Bracketed figures are extrapolated (see page 205).

The maximum once-in-50-year wave height of just over 35 m (about 115 ft) is associated with a once-in-50-year mean wind speed of 72 kt having a duration of about 4 hours. The corresponding significant wave period is about 19 seconds. This maximum wave height compares with a once-in-50-year value of between 30 and 33 m to the west of the Shetlands taken from the map of 50-year design wave heights prepared by Draper and published by the Department of Energy.¹ Considering the various uncertainties involved this may be regarded as a satisfactory degree of agreement.

Acknowledgements. The author wishes to thank Mr R. Anderson-Jones who designed and wrote the necessary computer programs, and Mr L. Draper, Institute of Oceanographic Sciences, who kindly read a first draft of the paper and made some helpful suggestions.

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THE DISTRIBUTION OF RAINFALL OVER SUBCATCHMENTS OF THE RIVER DEE AS A FUNCTION OF SYNOPTIC TYPE

By C. A. NICHOLASS and T. W. HARROLD

Summary. Two years of data from a network of 63 tipping-bucket rain-gauges distributed over the 1000-km² catchment area of the upper portion of the River Dee have been analysed to derive relationships between the rainfall over subcatchments of area typically 60 km² (R_s) and that averaged over the entire area of the network (R). It is shown that the ratio R_s/R is dependent on the synoptic type and surface wind direction. Using these two parameters as inputs, the distribution of storm rainfall within the upper portion of the Dee Catchment could be forecast with adequate accuracy from an accurate quantitative forecast of the rainfall over the whole catchment area. The extent to which this conclusion can be applied to other areas is discussed.

Introduction. A network of 63 tipping-bucket rain-gauges is operated by the Water Data Unit and the Welsh National Water Development Authority as part of the Dee Weather Radar Project (see for example Harrold, English and Nicholass¹). These gauges provide data in 15-minute time periods over a 1000-km² catchment area of the upper portion of the River Dee in North Wales.

Two years of the data obtained have been used to determine relationships between subcatchment and catchment areal rainfalls for different synoptic weather types. The subcatchments vary in size from 20 km² to 104 km² (see Figure 1).

Such relationships may be of use to the forecaster and hydrologist, since they would enable forecasts of rainfall amounts over large areas, such as those which will be available eventually from computer models, to be used in estimating rainfall over the much smaller areas which are of importance to hydrologists, particularly in the efficient operation of regulating reservoirs.

Although the data demonstrate only the relationships which exist within the Dee Catchment, ways in which similar climatological rules could be investigated in other river catchment areas are discussed.

Analysis and results. For the two-year period ending April 1974 the synoptic type and surface wind were classified by reference to the *Daily Weather Report*. The surface wind velocity over the Dee Catchment was estimated from

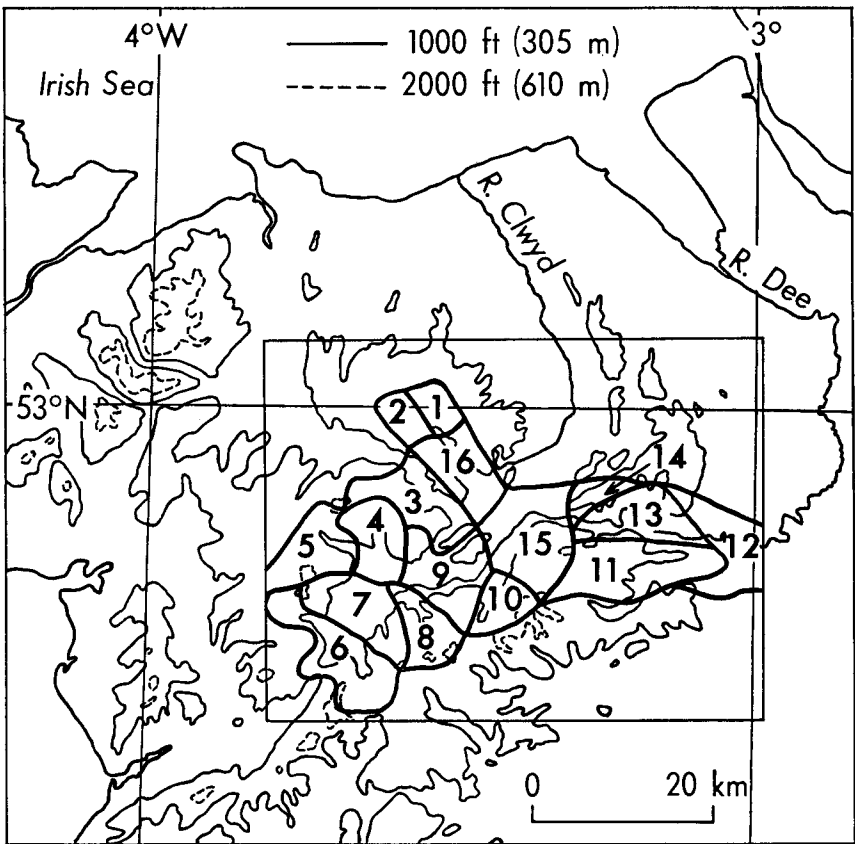


FIGURE 1—MAP SHOWING THE LOCATION OF THE RIVER DEE CATCHMENT AREA AND THE 16 SUBCATCHMENTS REFERRED TO IN THE TEXT

nearby observations in four categories of wind direction, N to E, E to S, S to W, and W to N, and three categories of speed, 0–15 kt, 15–25 kt, and more than 25 kt. (The possible situation that all of the relevant surface winds were exactly south or west for example, thus making classification difficult, did not occur in this analysis.)

Early in the analysis it was found that when the surface wind speed was more than 15 kt the actual speed was not a significant factor in determining the distribution of rainfall within the Dee Catchment. (Not enough heavy rainfalls occurred when the wind speed was less than 15 kt to allow a decision on the importance of light wind speeds to be made.) Therefore only surface wind direction on a four-point compass (SW means winds between S and W) is discussed here.

Six synoptic types were classified: pre-warm-front; warm sector (including rain ahead of cold fronts); post-cold-front; occlusions; cyclonic rain not associated with well-defined frontal systems; and showers (with or without thunder) not associated with any other type. Periods during which the synoptic type and surface wind direction were constant are referred to as weather types in the following; they lasted between 3 and 36 hours approximately. For each weather type the areal rainfall for the whole of the Dee Catchment and for each of 16* subcatchments was computed by the method described by English.² Occasions when snow may have fallen or may have been lying in the gauges have not been included in the analysis.

Graphs were plotted of catchment rainfall against subcatchment rainfall for the different weather types. They showed that a linear relationship existed between the two parameters, so a line of best fit, correlation coefficient and standard error of the estimate were calculated for each subcatchment and weather type.

Examples of the data from two subcatchments for warm-sector rain with south-west winds are shown in Figure 2. The total number of rain periods in this category was 52. These graphs and those for each subcatchment for this weather type are summarized in Table I. The scatter about the line of best fit is expressed in two ways. In column 4 the standard error of estimate of R_s is shown in millimetres. In column 5 the error is expressed as a percentage of the mean fall over each subcatchment calculated from the 52 occasions. Averages of the errors shown in columns 4 and 5 are 2.3 mm and 33 per cent respectively. These values are indicative of the errors to be expected in a forecast of subcatchment rainfall, and they show that in the particular type of situation under consideration, the distribution of the rainfall over the subcatchments could be predicted with a fairly high degree of accuracy, provided that the rainfall over the entire catchment could be correctly forecast.

Table II summarizes some of the statistical parameters for the 10 weather types in which sufficient rain fell for significant regression equations to be calculated. Data for three subcatchments, which are representative of the 15, are presented. These results show that the scatter in the relationships in frontal rains is generally similar to those in Table I. Not surprisingly the scatter is

*Note: The results from subcatchment 12 will not be discussed since the small number of gauges in the area made it difficult to obtain accurate areal estimates over the subcatchment; the catchment estimate should not be significantly influenced by the sparser network in this region.

TABLE I—WARM-SECTOR RAINS WITH SOUTH-WEST WINDS

Subcatchment	Slope of line of best fit R_s/R	Correlation coefficient	Standard error of estimate of R_s (S_s) millimetres	S_s/\bar{R}_s per cent
1	0.66	0.85	2.3	42
2	0.73	0.88	2.2	38
3	1.01	0.95	1.8	24
4	1.35	0.97	2.0	20
5	1.76	0.89	5.2	38
6	1.74	0.92	4.2	32
7	1.55	0.96	2.5	23
8	1.44	0.97	2.2	25
9	1.12	0.99	0.9	13
10	1.04	0.96	1.9	29
11	0.71	0.88	2.3	54
13*	0.52	0.86	1.8	54
14	0.59	0.89	1.8	48
15	0.77	0.96	1.3	29
16	0.77	0.95	1.5	27
Average values			2.3 mm	33%

* Subcatchment 12 has been omitted.

largest in the eight occasions of showery rain which did not fit into one of the other classifications. In this class there appeared to be little or no systematic effect.

The results also show that the orographic effects are strongly dependent on weather type. The variability of rainfall on the scale of subcatchments is most marked within warm sectors and least marked ahead of warm fronts when the surface wind is south-westerly (see Table II). These findings are consistent with the conclusions of Browning *et alii*,³ which were based on a very limited, but extensively analysed, number of cases.

The preceding statistical results have been computed for rainfall totals from periods of constant weather type. Falls from a few of the wetter storms shown in Figure 2 have been subdivided into hourly totals to investigate the extent to which these climatological rules are applicable to shorter periods within the storms. An example of the results obtained is shown in Figure 3. The line of best fit has a slope of 1.57 with a standard error of estimate (S) of 0.82 mm and an S/\bar{R}_s of 30 per cent. So even on this short time-scale the distribution of rainfall can be predicted to a quite high degree of accuracy, provided that the large-scale rainfall can be forecast perfectly over the whole catchment.

Implications. The results of this investigation show that in general the amount of rain falling in a given synoptic situation over any subcatchment of the upper portions of the River Dee is closely related to the rainfall over the entire catchment. That is to say, given the large-scale (synoptic-scale) precipitation, the topography is by far the most important factor in controlling the distribution of rainfall in this area. The finding has important implications in forecasting rainfall amounts over subcatchments for hydrological purposes. Evidently the accuracy of forecasts of rainfall on the scale of subcatchments depends primarily

TABLE II—VARIATION OF SLOPES OF LINES OF BEST FIT FOR VARIOUS SYNOPTIC TYPES

Synoptic type	Wind direction	Number of observations	Subcatchment 6			Subcatchment 9			Subcatchment 14		
			R_6/R	Standard error of estimate (S_6) mm	S_6/\bar{R}_6 per cent	R_9/R	Standard error of estimate (S_9) mm	S_9/\bar{R}_9 per cent	R_{14}/R	Standard error of estimate (S_{14}) mm	S_{14}/\bar{R}_{14} per cent
Pre-warm-front	SE SW	13	0.98	2.9	24	1.03	0.7	9	0.94	1.6	30
		22	1.71	3.3	36	1.09	0.7	15	0.68	1.2	51
Warm sector	SE SW	9	2.50	4.7	28	1.05	0.8	9	0.46	1.9	38
		52	1.74	4.2	32	1.12	0.9	13	0.59	1.8	48
Post-cold-front	SW NW	19	1.33	2.6	33	0.90	1.2	21	0.72	1.5	32
		19	1.29	1.5	29	0.99	0.9	23	0.86	1.0	27
Cyclonic rains	SW + NW SE + NE	24	1.10	3.0	29	1.11	1.0	14	0.76	2.1	41
		18	1.14	3.3	25	1.07	3.7	32	0.91	3.5	33
Occlusions	Various	21	1.17	3.4	36	0.88	2.3	35	0.65	1.9	38
Showers and thunderstorms	Various	8	0.03	3.4	79	2.22	2.2	38	1.19	2.8	69

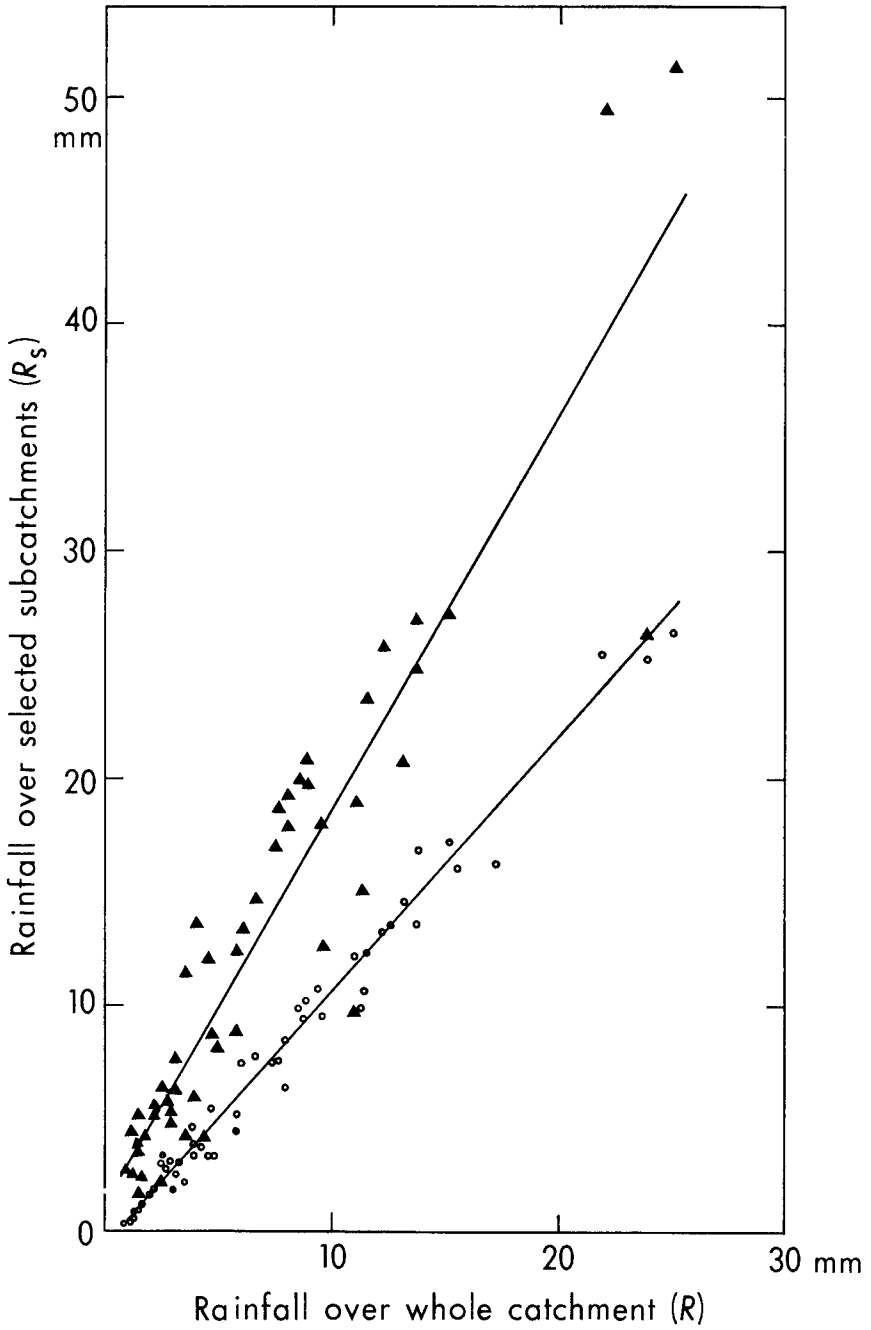


FIGURE 2—RAINFALL IN AREA 6 (\blacktriangle) AND AREA 9 (\circ) PLOTTED AGAINST AVERAGE RAINFALL FOR ENTIRE AREA OF THE NETWORK (R) FOR WARM-SECTOR RAINS (AND RAIN AHEAD OF COLD FRONTS) WITH SOUTH-WEST WINDS

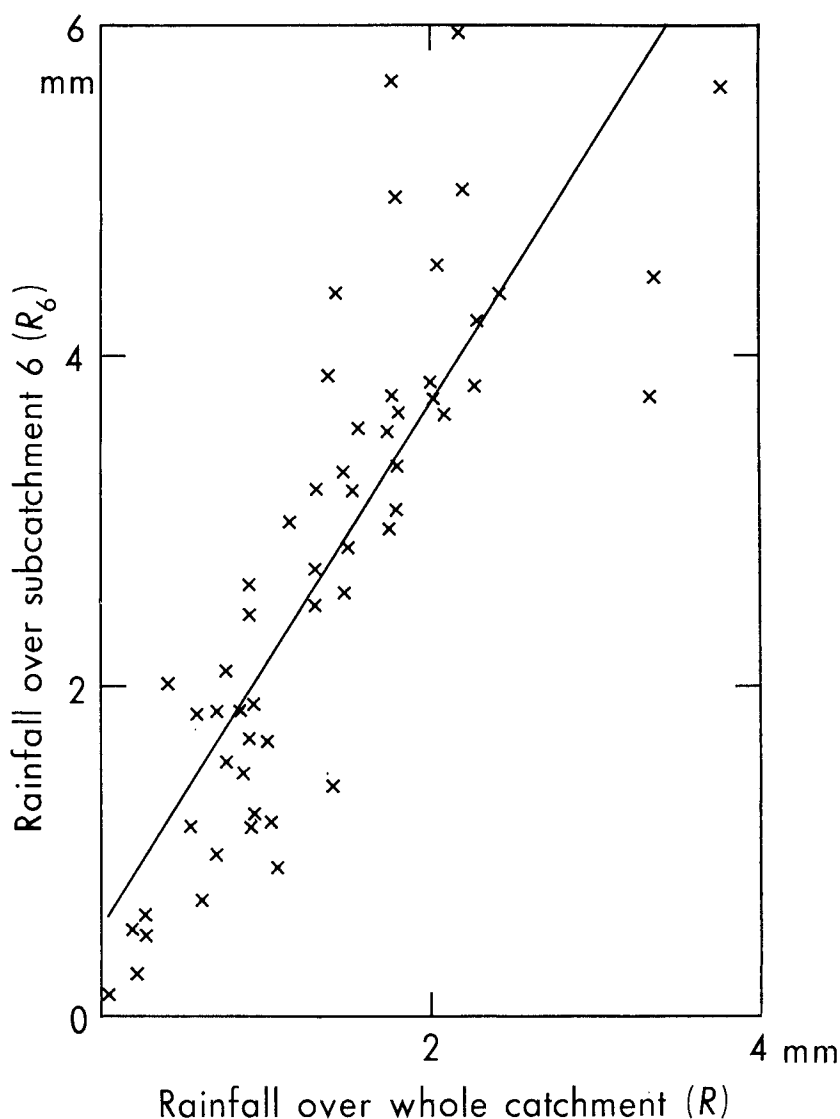


FIGURE 3—HOURLY RAINFALL IN AREA 6 (R_6) PLOTTED AGAINST HOURLY AVERAGE RAINFALL (R) FOR A SAMPLE OF THE WARM-SECTOR RAINS WITH SOUTH-WEST WINDS

on the accuracy with which the rainfall amounts over the entire catchment of 10^3 km^2 can be forecast. With this proviso that the large-scale rainfall can be accurately forecast, the distribution of rainfall within the catchment is reasonably predictable, particularly in frontal situations which produce by far the largest portion of the total rain in the area. The main exception occurs in

showery conditions. In addition, a mesoscale rain band not related to the topography (at least in its immediate vicinity) may occasionally dominate the frontal rainfall pattern for a period. Further research is needed in order to identify in advance occasions when such exceptions might occur.

The data were gathered over one particular hilly area. It is not known to what extent analogous synoptic climatological relationships apply in other hilly areas. However, the topography of the catchment of the Upper Dee is quite complex, with mountain ranges at several different orientations, so that the effects of the topography are complicated. Hence there is every reason to expect that similar well-defined relationships exist in other hilly areas. Unfortunately the data needed to determine such relationships cannot easily be obtained, since rainfall totals over small areas are required for periods of 'constant' synoptic type. Ways in which such data might be obtained are:

(a) to use existing autographic rain-gauge data. However, the density of autographic gauges is too sparse in almost all hilly regions to determine sub-catchment rainfalls sufficiently accurately;

(b) to obtain additional rain-gauge data. This could be done by greatly increasing the density of autographic rain-gauges in areas of interest. However, the cost of collecting and analysing the data from an adequate network of such gauges in hilly terrain is high—£40 000 per annum for the Dee network. An alternative, simpler, means of obtaining the necessary data is to use quantitative rainfall measurements derived from weather radar (Harrold *et alii*¹). The feasibility of doing this will be investigated using a mini-network of three quantitative weather radars during 1975 (Taylor and Browning⁴), but this network will only be operated occasionally for special research studies. A routine operational network of radars, such as discussed by Dee Weather Radar Project⁵ would be required if radar were to provide the amount of data needed to determine climatological relationships over an extensive region; and

(c) to use a numerical model of the topographic effects on rainfall. Such a model has been described by Collier,⁶ and Table III shows ratios of R_s/R over subcatchments of the Dee derived from this model in moving baroclinic disturbances, together with those from the rain-gauge network, for south-westerly winds. The average difference in R_s/R between these entirely different techniques is 21 per cent. However, it is not yet certain to what extent the model can be applied in other hilly areas; some independent data are required to investigate this.

It must be stressed that synoptic climatological relationships between rainfall amounts over subcatchments (typical area 60 km²) to that over 1000 km² will only be of practical value if the rainfall amount over the 1000 km² can be accurately forecast. Possible methods of achieving reliable forecasts on the scale of 1000 km² are:

(a) to use existing numerical techniques with a smaller (mesoscale) grid length. It is not yet known what the smallest scale of accurate forecasts is but it seems improbable that it will be less than 10³ km² in hilly terrain;

(b) to use climatological relationships similar to those described on page 210 to link the smallest scale accurately forecast in (a) to the scale of 10³ km² (and hence 10² km²). Suitable data do not exist at present for the determination

of relationships on this larger scale, but some should be forthcoming from the mini-network of research radars; and

(c) to use a parameterization such as Collier's⁶ model to estimate the precipitation on a scale of 10^3 km^2 from an input of the larger-scale wind and humidity field, derived for instance from (a). This has been shown to be a successful technique over the Dee Catchment in moving baroclinic systems, using actual, rather than forecast, input parameters.

TABLE III—COMPARISON OF PREDICTED AND ACTUAL CLIMATOLOGICAL RATIOS FOR WARM-SECTOR RAINS WITH SOUTH-WEST WINDS

Subcatchment	R_s/R computed by Collier's ⁶ model	R_s/R measured by rain-gauges	Computed ratio measured ratio per cent
1	0.83	0.66	126
2	0.75	0.73	103
3	0.92	1.01	91
4	1.41	1.35	105
5	1.83	1.76	104
6	1.67	1.74	96
7	1.50	1.55	97
8	1.08	1.44	75
9	0.92	1.12	82
10	1.25	1.04	120
11	1.08	0.71	152
13	0.67	0.52	129
14	0.83	0.59	141
15	0.92	0.77	119
16	1.16	0.77	151

Mean absolute percentage difference = 21%

Conclusions. The analysis has shown that in most circumstances over the upper portion of the River Dee forecasts of the rain over subcatchments of area 20–100 km^2 could be forecast if there were a means of forecasting accurately over an area of 1000 km^2 . It is considered that a similar conclusion would apply to other hilly terrain. Thus, if a method of forecasting rainfall over the larger area were developed this would also enable the hydrological requirement of quantitative rainfall forecasts over the smaller areas to be met.

However, there are several other forecasting requirements, for instance variations of rainfall intensity with time and also localized storms and stationary mesoscale rain bands which are not handled by the climatological rules. To meet these full requirements, it will probably be necessary to use results of the type presented in this paper in conjunction with real-time data from an operational network of weather radars.

Acknowledgements. The data used in this paper were collected and partly processed by the Welsh National Water Development Authority and the Water Data Unit, Reading as part of the Dee Weather Radar Project. The authors would like to acknowledge the assistance of Mr P. S. Shier (vacation student) in the analysis.

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CONFERENCE ON 'ENGINEERING HYDROLOGY TODAY', LONDON, 18-20 FEBRUARY 1975

By R. MURRAY

A conference on 'Engineering Hydrology Today' was held at the Institution of Civil Engineers in London from 18 to 20 February 1975 under the joint sponsorship of the Institution of Civil Engineers, the Institute of Hydrology, and the organizing committee of the International Hydrological Decade. The conference set out to review the contributions to the International Hydrological Decade (1965-74) made by the United Kingdom, with particular emphasis on results of relevance to engineering.

The conference was opened at 2 p.m. on the 18th by Lord Nugent, chairman of the National Water Council, who spoke briefly about the reorganization of the water industry which took place on 1 April 1974 as a consequence of the Water Act 1973. It was appropriate that Sir Norman Rowntree, erstwhile Director of the former Water Resources Board, which ceased to exist on 31 March 1974 as a result of the Act, should give the last talk on 'Summing-up and a look to the future'. Between the contributions of Lord Nugent and Sir Norman Rowntree, the conference was organized into six sessions which dealt with Organization, Instrumentation and Techniques, Meteorology, Flow Models, Flow Frequency Estimation, and Storage. There were three papers directly concerned with meteorology, namely (a) 'Determining precipitation, evaporation and soil moisture' by Dr. J. C. Rodda (Water Data Unit) and Mr J. F. Keers (Meteorological Office), (b) 'The variability of precipitation and evaporation' by Mr J. F. Keers and Dr J. C. Rodda and (c) 'Estimation of irrigation needs' by Mr B. G. Wales-Smith (Meteorological Office). All three papers were well received by an audience of nearly 200.

Dr Rodda, who introduced the first paper, demonstrated progress by the developments in measuring rainfall by radar (a major part having been played by the Meteorological Office team in the co-operative Dee Weather Radar Project) and in neutron probes, although Dr Penman was quick to point out that neutron probes were not novel to the Decade. Dr Rodda had to confess,

however, that rainfall continued to be measured for the most part by conventional gauges, but mentioned the Kew gravimetric gauge as a standard against which other types of gauge could be compared. There was lively discussion about the accuracy with which rainfall was measurable in different regions: in particular Mr Reynolds of the North of Scotland Hydro-electric Board thought that Dr Rodda was much too pessimistic in quoting a 20 per cent difference between readings in hilly terrain from the Meteorological Office Mk 2 rain-gauge sited in the standard way and the pit gauge with its rim at general ground level. Support for the accuracy of readings from the Mk 2 gauge, properly sited, came from Dr Penman and others. Nevertheless, it was felt that the problem of accurately measuring rainfall was still with us, especially over difficult terrain, although it was recognized that useful areal estimates could be obtained by radar. Snow measurement continued to be an unsolved problem. The need to improve the reliability of recording gauges, which generally have too high a failure rate, especially in freezing weather, was stressed by several delegates.

Mr Keers introduced the second paper but concentrated mainly on rainfall variability. A useful account was given of the different time and space scales of rainfall variability, with some reference to the precipitation mechanisms and underlying causes. He drew attention to some results of the work done by British radar meteorologists, notably Browning and Harrold, during the Decade, and referred briefly to the Meteorological Office's 'Project Scillonian' and the recent Global Atmospheric Research Programme Atlantic Tropical Experiment (GATE) during the summer of 1974, in which the United Kingdom, notably the Meteorological Office through the Meteorological Research Flight, played an important part. Mr Keers also touched upon the recently completed *Flood Studies Report*, but detailed discussion of this report was reserved for a conference at the Institution of Civil Engineers in May 1975.

Mr Wales-Smith surveyed a very wide field in his written paper but sensibly curtailed his spoken presentation and concentrated for the most part on studies in hand within the Meteorological Office. These studies concerned improvement of the 'Estimated Soil Moisture Deficit' (SMD) bulletin by means of the incorporation of a more realistic land-use model and by an improved computer-based system for accessing all types of up-to-date data needed for full exploitation of the Penman formula which constituted the scientific basis of the Meteorological Office's SMD bulletin. Brief reference was also made to rainfall deficiency studies and to other investigations. All such work should make it feasible to monitor soil moisture deficits more efficiently throughout the country and should help therefore in the monitoring of irrigation needs, especially if weather forecasts were sensibly used in connection with the latest SMD information.

The two papers presented by Keers and Wales-Smith were discussed together and provoked a lively discussion amongst hydrologists and engineers. At one point there was danger of the discussion straying too far into the field reserved for discussion at the conference on the *Flood Studies Report* in May 1975, but this clearly indicated the need felt by engineers for information on flood-producing rainfall, especially rainfall of short duration, information which is important in planning drainage systems. The need for informed advice on rainfall to engineers engaged on projects in hilly areas was mentioned. The lack of information on the variability of evaporation, comparable to the information on the variability of precipitation, was also mentioned in the discussion. Several

speakers clearly indicated the importance of work on evaporation and on soil moisture deficits to water resources management and indeed to civil engineers. Mr N. J. Cochrane (Sir William Halcrow and Partners) stressed the need for more information about evaporation and soil moisture conditions. Incidentally Mr Cochrane mentioned that neutron probes had been used—without much success owing to difficulties of maintenance and power supply—in two road-building projects in Africa many years ago. However, there was little doubt that under reliable management neutron probes were now reliable instruments.

Other important papers by hydrologists and engineers on 'Catchment modelling to estimate flows', 'Open-channel hydraulics', 'Flow frequency estimates', 'Groundwater yield estimates from models' and 'Assessment of surface water sources' were not so directly of interest to meteorologists, although the meteorological input (precipitation and evaporation) is of great importance. It was interesting to a meteorologist to learn that some of the engineers and practical hydrologists were rather sceptical about the value of complicated mathematical models and seemed to prefer empirical models, based on data and experience. There was also a feeling of distrust among some delegates of synthetic-data generation, especially in view of the amount of rainfall data, and to a less extent stream-flow data, available in the United Kingdom.

The conference was particularly appreciated by the three Meteorological Office representatives who were able to meet engineers and hydrologists and to learn about some of their practical problems and their meteorological requirements, as well as to enjoy accounts of some British achievements in hydrology during the recent Decade.

PUBLICATIONS RECEIVED

The following have been received from the Meteorological Institute of the University of Thessaloniki:

Meteorologika 36: *Nature of the diurnal variation of atmospheric pressure in Thessaloniki.*

By T. J. Makroyannis. 1974.

Meteorologika 37. *Cooling power and weather types in Thessaloniki.* By Chr. J. Balafoutis. 1974.

Meteorologika 38: *On the effect of ground relief upon sunshine duration on Mount Olympus—Greece.* By G. C. Livadas and V. A. Semertzidis. 1974.

Meteorologika 39: *On the annual variation of air temperature in Thessaloniki.* By A. A. Flocas and A. Arseni-Papadimitriou. 1974.

Meteorologika 40: *Contribution to the study of air temperature in Thessaloniki.* By A. Arseni-Papadimitrou. 1974.

Meteorological Magazine: price increases

As from July 1975 the price of an issue of the *Meteorological Magazine* will be 40p and the annual subscription will be £5.46 including postage.

NOTES AND NEWS

Retirement of Mr J. M. Craddock

On 4 June 1975 Mr James Marston Craddock retired from the Meteorological Office after 33 years' service. For the previous 16 years he had been a Special Merit Senior Principal Scientific Officer concerned with the application of statistics and computers to long-range weather forecasting.

Mr Craddock joined the Office in 1942 on secondment from the Inland Revenue Department, having previously taken a first-class degree in mathematics at Cambridge University where he was a scholar of Magdalene College, and spent the next five years of his career as a forecaster. After a short spell at Prestwick he was posted to the upper-air bench at Dunstable. He was then commissioned as a Flight Lieutenant in the Royal Air Force and posted to the Far East where he spent about a year in Singapore before moving to Butterworth.

On demobilization in 1947, Mr Craddock, having decided that he would get more satisfaction from meteorological research than from returning to the Inland Revenue, was posted as a Senior Scientific Officer to Dunstable and was one of the first members of Dr Sutcliffe's forecasting-research group in the Napier Shaw Building. Mr Craddock had clearly found his niche in life and, apart from a two-year spell in 1953-54 when he was posted to the Central Forecasting Office as a senior forecaster on his promotion to Principal Scientific Officer, he continued to work in the research branch connected with long-range weather prediction until his retirement. In 1959 he obtained a well-deserved special merit promotion to Senior Principal Scientific Officer. In addition he received the L. G. Groves and Darton Prizes in recognition of his scientific ability.

Two of Mr Craddock's major achievements in the Office have been the development of sound statistical methods for use in meteorological research and the application of computers to the operational and research work of the Synoptic Climatology Branch. In the statistical field Mr Craddock has made important contributions on topics such as the analysis of time series and the application of principal component analysis to meteorological problems. In the computer field he has been largely responsible for building up a large long-range data bank and for developing the METOCODE language which has considerably reduced the amount of programming effort required to permit statistical programs to be run on the computer. In addition, Mr Craddock has been a World Meteorological Organization consultant concerned with the collection, storage and cataloguing of meteorological literature and data.

We all wish Mr and Mrs Craddock many years of happy retirement.

F. H. BUSHBY

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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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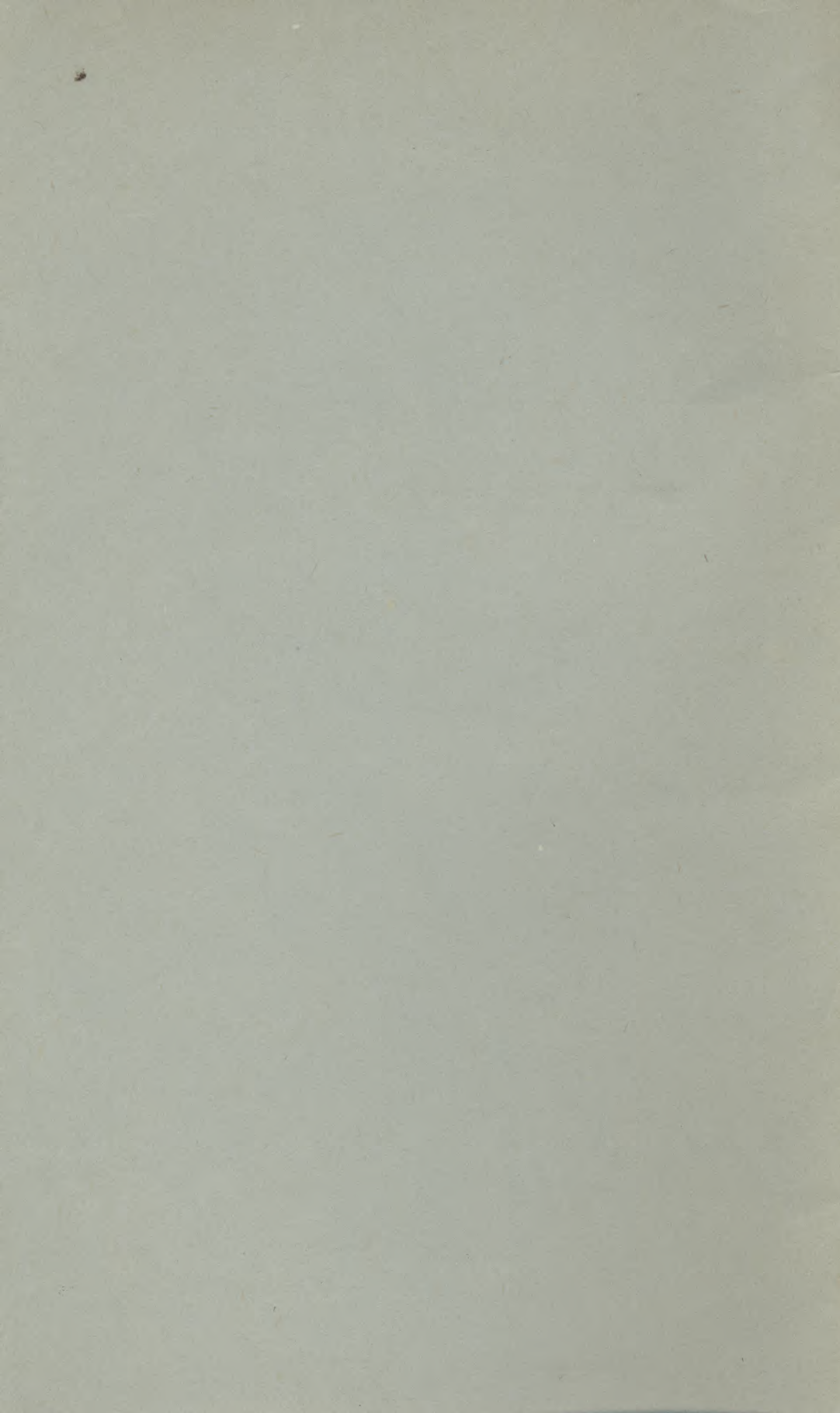
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INTENSITY-TIME PROFILES OF HIGH-INTENSITY RAINFALL

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Summary. Data from 77 high-intensity rainfall events, observed by rapid-response rain-gauges, have been combined to produce an average intensity-time profile. The shape of the profile is independent of peak rainfall rate. The effect of the rain-gauge sampling time on the profile has been examined.

Introduction. Knowledge of the statistical properties of high-intensity rainfall is needed for estimating the attenuating effect of rain on terrestrial or earth-space millimetric radio links and predicting the performance of some radar systems. It is also useful to workers investigating erosion and drainage.

In many cases, a study of near-instantaneous rainfall rates is required but few experimental measurements have been made. Often, only clock-hourly or daily rainfall amounts are available and methods have been developed in which short-period rainfall rates can be deduced from the longer-period rates. Briggs¹ has derived an average profile of shower intensity at a point against time for the 15 heaviest showers recorded during experiments at Cardington² in which use was made of a network of open-scale recording rain-gauges the records from which were analysed to give falls in successive 2-minute intervals, and he gives a method of deducing the high-intensity, short-period falls when records are available for rates up to about 10 mm/h. Briggs and Harker³ have used the results of a similar analysis from another network at Winchcombe to derive factors which can be applied to estimate, from clock-hourly statistics, the probability of occurrence of short-period rain intensities.

Since late 1969, several rapid-response rain-gauges⁴ have been in operation at the Appleton Laboratory, Slough, in conjunction with measurements of the effect of attenuation by rain on experimental millimetric radio links. These gauges produce records of rainfall amounts collected over successive 10-s intervals. On 77 occasions, showers, thunderstorms or the passage of cold fronts produced rainfall with peak values greater than 20 mm/h. Some statistical values derived from these events are presented here.

Selection of events. The term 'rainfall event' or 'event' is used here to mean a fall of rain lasting no more than 15 to 20 minutes, due either to local convective activity or to the passage of a vigorous trough of low pressure, in which the intensity rises from zero or a very small value to a maximum and then drops away to zero again. Some examples of intensity-time profiles, produced directly

from observations of rainfall measured over 10-s intervals are presented in Figure 1. Figure 1(a) shows a shower with a simple structure but Figures 1(b), (c) and (d) show profiles which are complex. They contain a number of individual peaks, some of them quite well defined.

It was decided that two criteria should be met for the inclusion of a profile in the analysis:

- (a) the peak intensity had to be greater than 20 mm/h, and
- (b) because of the sampling error inherent in the performance of any rain-gauge,⁵ a profile must have two consecutive 10-s readings in excess of 20 mm/h.

The duration of an event was easy to define when the rain rate fell smoothly away to a continuous value of zero on either side of a peak value. This happened on 52 occasions on the rising side of a peak and 38 occasions on the falling side of a peak. In the remainder, the duration of the event was taken as defined when the rate fell to or below a preset level for a given length of time. The preset level chosen was 5 per cent of the peak value, or 2 mm/h, whichever figure was the higher, and the length of time was set at 30 s. Only three events would have been split into two if a time of 20 s had been chosen.

For events where the rate did not fall to zero, a small adjustment was made to each point in the profile by subtracting the average rainfall rate over the 30-s periods used to define the duration of the event.

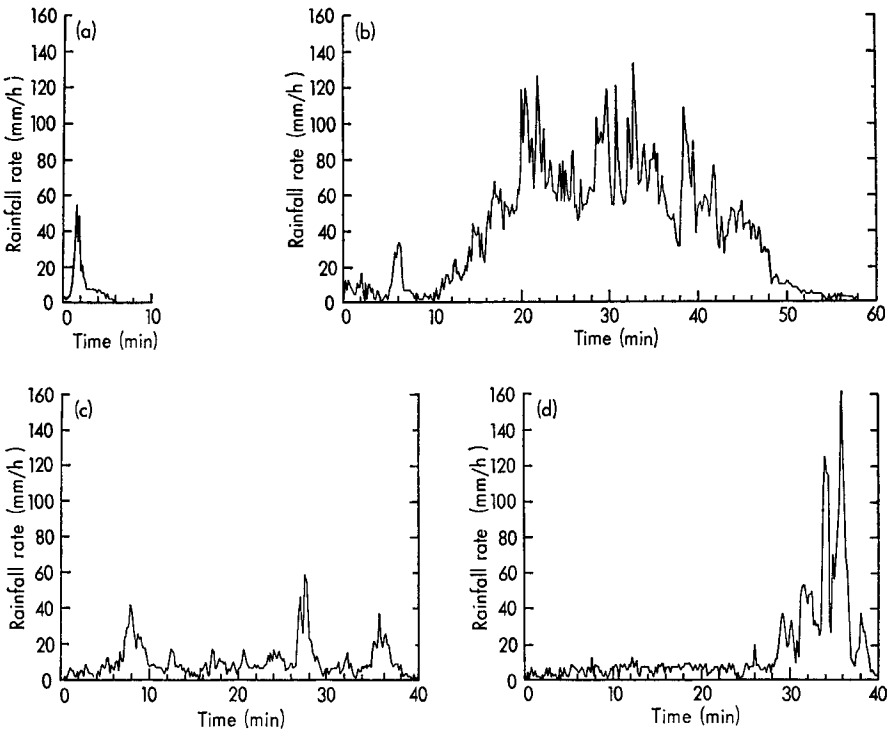


FIGURE 1—EXAMPLES OF SHOWER PROFILES

(a) shows a simple structure, while (b), (c) and (d) are complex structures.

A total of 77 events with peak rates in excess of 20 mm/h satisfied the above criteria. The numbers of events with peak values within specified levels, and for durations of specified lengths, are given in Figures 2 and 3.

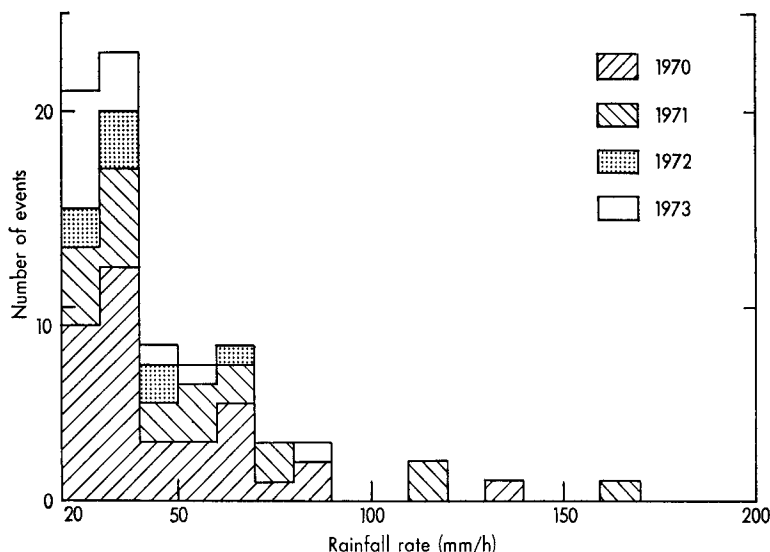


FIGURE 2—NUMBERS OF EVENTS WITH PEAK VALUES WITHIN SPECIFIED LEVELS

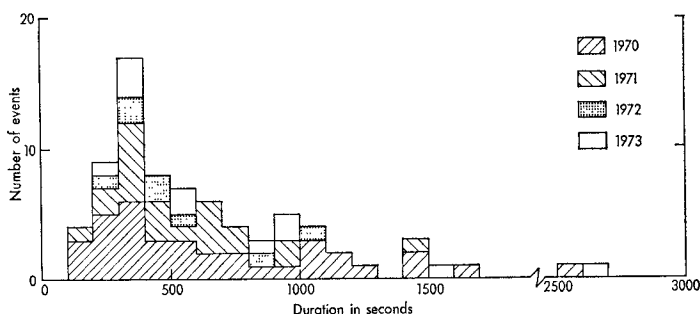


FIGURE 3—DISTRIBUTION OF DURATIONS OF EVENTS

Method of analysis. For each event the intensities in all the 10-s intervals were expressed as fractions of the peak value. The mean profile was then obtained by averaging the fractions at successive intervals of 10 s before and after the peak of each of the 77 events.

To obtain an estimate of the scatter of the values around the mean, the standard deviation (σ) was determined for each 10-s interval.

Intensity-time profiles. The mean profile, and those corresponding to $\pm 1 \sigma$ are shown in Figure 4 for times from -550 s to 550 s from the peak. The width of the mean profile between points where the intensity is 50 per cent

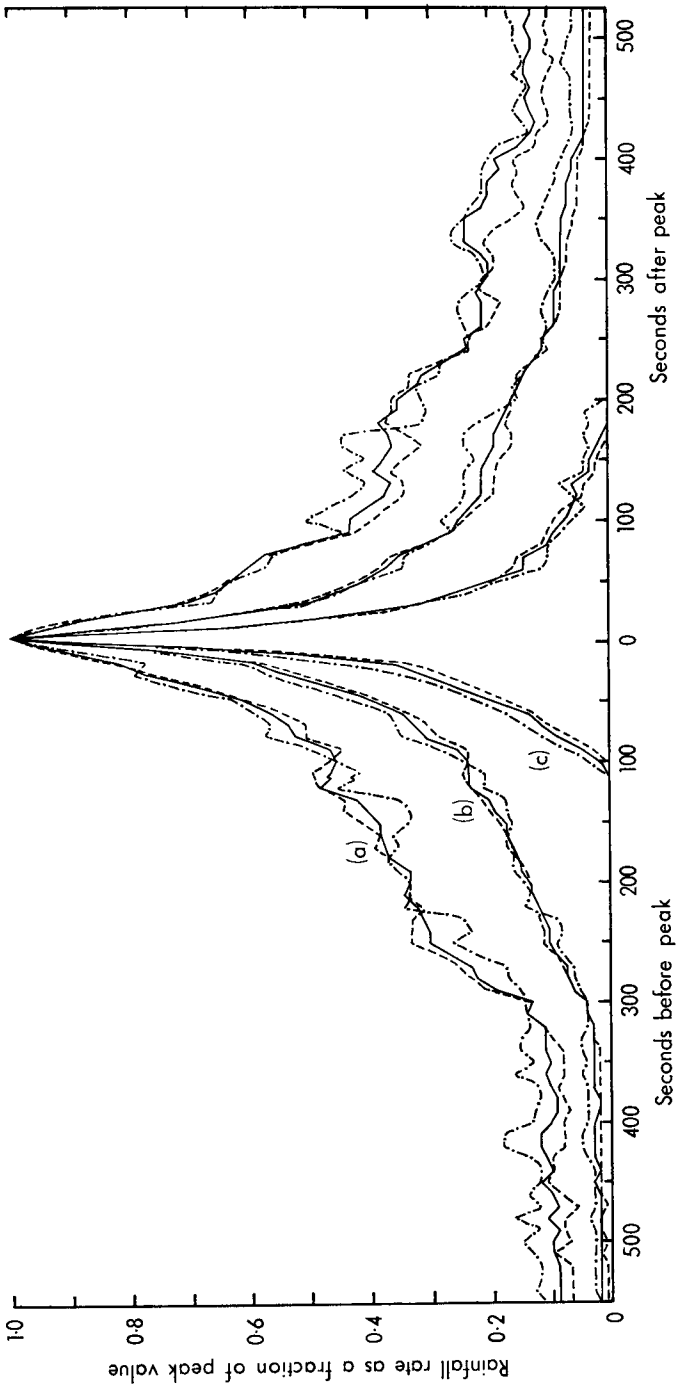


FIGURE 4—MEAN AND STANDARD-DEVIATION PROFILES FOR EVENTS WITH PEAK RATES IN EXCESS OF OR BETWEEN SPECIFIED LEVELS

- (a) mean profile $+ 1 \sigma$
- (b) mean profile
- (c) mean profile $- 1 \sigma$
- All events
- Events with peak values in the range 20 mm/h to 50 mm/h
- .-.- Events with peak values in excess of 50 mm/h.

of its peak value—which may be called the ‘half-width’—is about 67 s, and the average rainfall rate, using an arbitrary upper limit of 2100 s for the duration of the mean profile, is 9 per cent of the peak value.

The large variations from the mean profile arise from the different spatial extents and speeds of movement of the rain cells, and the fact that a single gauge records profiles along different chords of the various cells. Wind speeds at the 700-mb level for the events included in the analysis range from 3 m/s to over 40 m/s, but the spatial extents of the events are not known.

Variation of mean profile with peak intensity. Figure 4 also shows the mean and standard-deviation profiles for events with peak rates in excess of 50 mm/h, and for events with peak rates between 20 mm/h and 50 mm/h. There is no statistically significant difference between the profiles. This implies that in this range of rates the profile is independent of the peak value.

Too few events have been observed with rainfall rates much in excess of 50 mm/h for one to be able to say whether this independence applies for very intense peak values. For example, only 10 events have been observed with peak rates in excess of 70 mm/h, and this is a small number for statistical analysis. However, the mean profile obtained from these 10 events has the same half-width and the same average rainfall rate as the profile obtained from all 77 showers. This strongly implies that the model profile for events with peaks in excess of 70 mm/h will be the same as that for all others.

Effect of sampling time. The 10-s rainfall rates from the rapid-response rain-gauges have been averaged over longer periods to simulate gauges with longer sampling times. For the present study the results have been averaged to give 1-minute and 2-minute clock values for all events. The results were analysed in the same way as the 10-s data.

For the 1-minute values, events with 1-minute rainfall rate peaks in excess of 20 mm/h were chosen. However, in order to obtain a large enough sample for the 2-minute rates, a figure of 15 mm/h was used. The profiles obtained are shown in Figure 5 together with the 10-s values, and the 2-minute values from the profile derived by Briggs. The 2-minute profiles agree well. The average rainfall rate for the Slough 2-minute profile is 12.5 per cent of the peak value, again in good agreement with the figure of 12 per cent obtained by Briggs.

Conclusions. A mean profile has been derived for the variation with time of intense rainfall observed at a point over an interval of 10 s. It appears to be independent of peak rainfall rate and has a half-width of 67 s and an average rainfall rate of 9 per cent of the peak value. The extent of expected variation from the mean is indicated by the profile giving values for the mean $\pm 1 \sigma$.

The mean profile derived by simulating a 2-minute rain-gauge is in good agreement with previous work.

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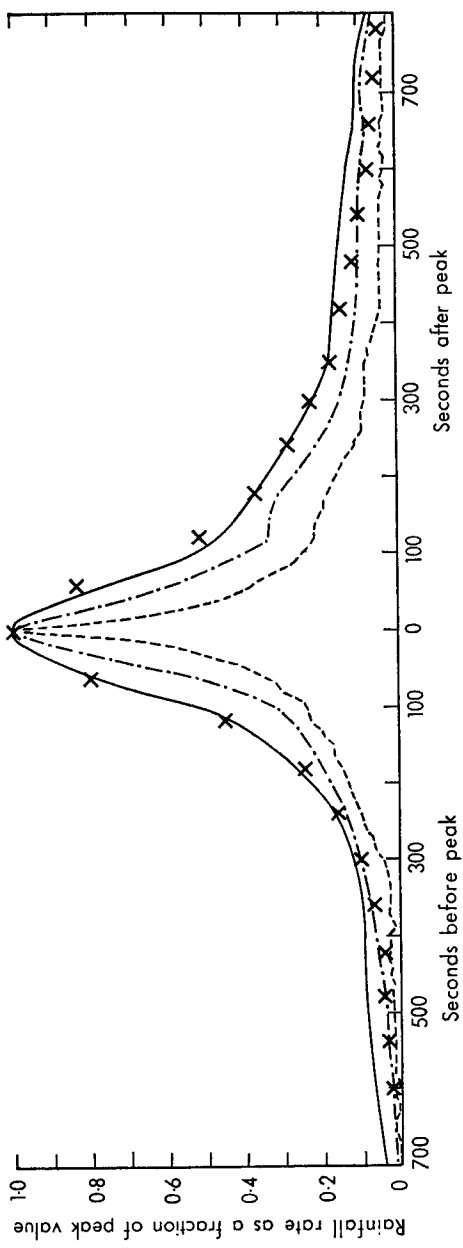


FIGURE 5—INTENSITY-TIME PROFILES FOR DIFFERENT SAMPLING TIMES

--- 10-s data -.-.- 60-s data — 120-s data x x x Briggs's data

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A NOTE ON TROPICAL STORMS IN THE ARABIAN SEA, OCTOBER TO DECEMBER 1972

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Summary. This paper describes the use made of satellite pictures for detecting and tracking the tropical storms which occurred in the Arabian Sea during the period from October to December 1972. The storm of 19-28 October is described in some detail.

Introduction. There are various definitions of 'tropical cyclones', 'tropical depressions' or 'tropical storms' and the terms themselves are subject to differing interpretations. However, setting aside these differences, it is well known that in an intense tropical storm the surface wind can exceed Beaufort force 12 (64 kt \approx 33 m/s); the weather is often violently disturbed, usually with torrential rain and occasionally accompanied by thunder and lightning. The frequency with which these storms occur varies very considerably over the different oceanic areas in the tropics, reaching a maximum in the North Pacific Ocean and a minimum in the Arabian Sea. These storms often originate just north of the Intertropical Convergence Zone (ITCZ) when it is displaced by at least five degrees of latitude from the equator. It is generally accepted that the sea temperature in the area must be at least 26.5°C.

In the Arabian Sea there are two seasons for tropical storms; firstly when the ITCZ is moving southwards in October to December and, secondly, when the ITCZ is moving northwards in May and June. Pedgley¹ showed that during the months October to December there were 30 storms over the whole Arabian Sea in the period from 1890 to 1950 (an average of one storm every two years). However, in the corresponding months of 1972 there were four storms which were all detected by means of satellite pictures from ESSA 8. Undoubtedly the use of the weather satellite will increase the frequency with which tropical storms are observed but the occurrence of four storms during October-December 1972 was probably not exceptional, since Pedgley¹ suggests that during 1902 five storms were observed over the Arabian Sea area. He also refers to 10 storms in 25 years (1943-67) which approached or crossed the Arabian coast. In October-December 1972 two storms approached the Arabian coast and one of these (19-28 October) even entered the Gulf of Aden, where only three or four storms were experienced during the period 1879-1944.²

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The storm of 19–28 October 1972. This tropical storm was first identified on 19 October and located at approximately 9°N 62°E on the ESSA 8 satellite picture; this provided the only evidence for the existence of a tropical disturbance. Daily pictures from ESSA 8 continued to provide the only information (apart from a few aircraft reports) with the help of which to locate the storm and forecast its progress. The track which it followed is shown in Figure 1. The cloud associated with the storm on 20 October can be seen in Plate I and its subsequent development in Plates II–IV.

The stage of development of the storm was estimated from the appearance and size of the cloud mass on the gridded satellite pictures. An estimate of the maximum surface winds associated with the storm was obtained from a nomogram produced by the Environmental Science Services Administration (ESSA)³ using stage of development and the diameter of the central cloud mass.

On 19 October the disturbance could only be classified as a dense cloud cluster. By the 21st the cloud mass was at least 6 degrees of latitude in diameter, with moderately concentric cloud bands. Much curved cirrus outflow was visible at the edge of the cloud mass, which was tending to become circular, but no 'eye' was discernible. A Stage X Category 2 storm had developed. Stage X storms are those with a centre within the cloud mass. The category (1–4) is determined from the degree of circularity of the curved and spiral bands. Only Stage X Category 3 and 4 storms have an 'eye'.

For the next two days (21–23 October) the storm continued to enlarge and a band of cloud 1600 kilometres long developed to the east. For about four days (19th–23rd) it moved broadly polewards at an average speed of $3\frac{1}{2}$ knots. It was slow moving on the 23rd, possibly moving eastwards. On the 24th (Plate III) it changed direction and moved quickly westwards, passing south of Ras Asir on the 25th, and into the Gulf of Aden by the 26th. It passed inland near Djibouti on the 27th (Plate IV). The storm averaged about 11 knots during its westward movement. The satellite pictures show that decay was quite rapid from the 25th to the 26th, but that a very dense cloud cluster with a diameter of about four degrees of latitude still remained when the storm crossed the coast on the 27th. This cloud dissipated almost completely by 28 October.

The centre of the storm approached to within about 900 km of Masirah on 24 October, and gave four rather cloudy days, with only a trace of rain on the 23rd—all the rain falling from unstable medium cloud in 20 minutes. At Salalah, where the centre was about 550 km to the south on the 23rd, south-easterly winds reached 40 knots with gusts to 57 knots between 11 and 12 GMT, and visibility was reduced at times to 50 m or less by rising sand. There was a further adjacent sandstorm on the 24th. Thunderstorms were reported in the vicinity of Salalah from 15 GMT on the 25th to 00 GMT on the 26th, when hail was reported. The rainfall recorded at Salalah was very close to the 1943–71 average for October of 8 mm. Farther west, at Aden, the storm gave 150 mm of rain, whereas the annual average rainfall there is only 40 mm. In Djibouti 230 mm of rain fell (average annual rainfall 130 mm) and there was considerable disruption and loss of life.

Upper-air observations in the vicinity of the storm were almost completely absent, the nearest radiosonde ascent being at Masirah, and the nearest pilot-balloon ascent being at Salalah. In addition, however, there were some wind measurements by aircraft on the eastern flank of the storm on 20, 21, 25 and

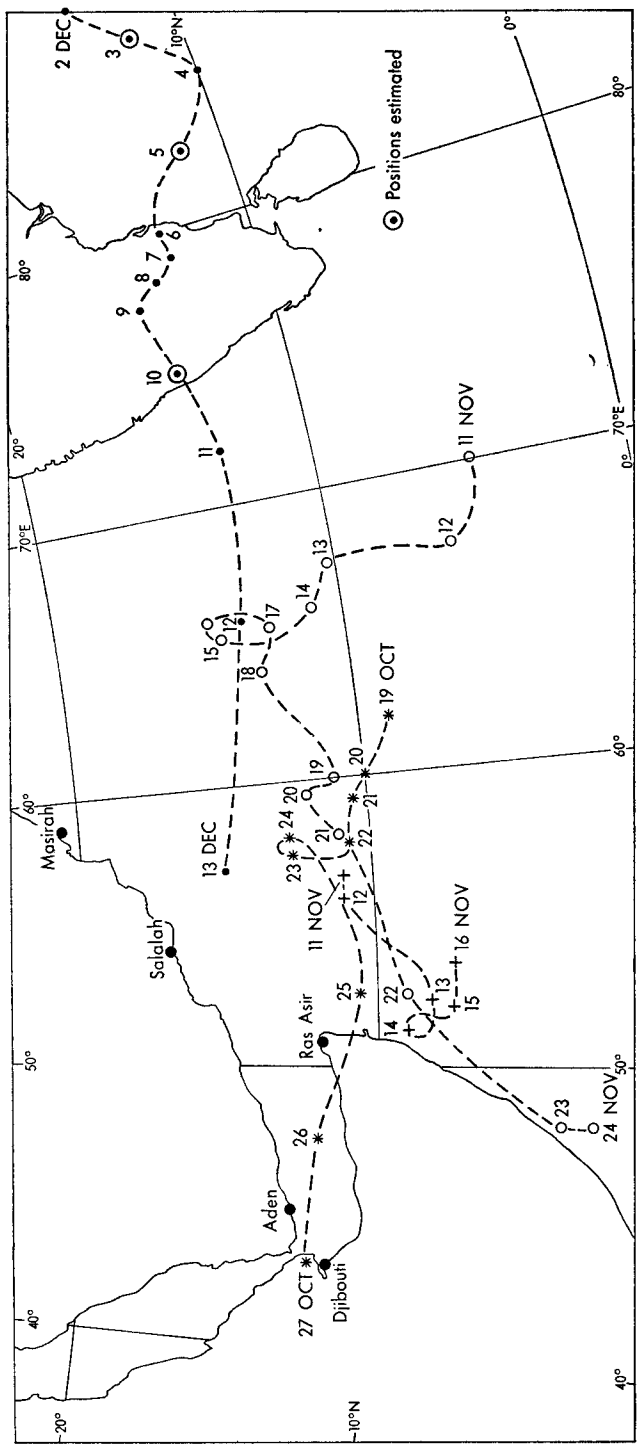


FIGURE 1—TRACKS OF FOUR TROPICAL STORMS OVER THE INDIAN OCEAN AREA—OCTOBER–DECEMBER 1972

26 October. Using this admittedly meagre amount of information it is possible to suggest a likely sequence of events at the 300-mb and 200-mb levels. On 19 and 20 October the storm moved slowly north-west and west as it emerged from the upper equatorial easterly flow. From the 21st to the 23rd a slow movement to the north and north-west continued around the western edge of the subtropical high. However, from the 22nd onwards 300-mb and 200-mb heights were rising over Arabia ahead of a marked upper trough extending southwards over the Red Sea. By the 23rd a considerable ridge had built up over Arabia, and by the 24th an anticyclonic circulation had developed over south-west Arabia. The easterly on the southern side of the upper high cell steered the storm into the Gulf of Aden.

Other storms during October–December 1972. The tracks of the other three storms of the October–December 1972 season are shown in Figure 1. These also were obtained from the daily ESSA 8 pictures only. The movements are often erratic and complicated, whilst the development and decay are very difficult to predict. It must be remembered that surface and upper-air reports from ships or aircraft are often completely absent over the Arabian Sea.

Conclusion. In this paper only four storms have been considered and the sample is too small to form the basis of any reliable forecasting rules regarding their movement and development over the Arabian Sea. However, it is possible to say that, in the main, these storms conformed to the following conditions:

- (a) Fast movement was usually associated with decay (two out of three storms).
- (b) Slow movement usually indicated intensification (two out of three storms).
- (c) Poleward movement indicated intensification (two out of three storms).
- (d) Storms over land decayed.

The occurrence of these Arabian Sea storms during October–December 1972 highlighted the value of weather satellites for the early detection of tropical storms and for forecasting their subsequent movement and development in an area of very sparse meteorological data. Continued regular surveillance of the area by weather satellite is likely to show an increase in the average previously reported frequency of occurrence of tropical storms over this particular sea area, but of more practical importance is the fact that meteorologists are now in a position to improve on the advice and warnings hitherto given over the Arabian Sea air routes and the adjacent coastal regions.

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OPTIMUM AVERAGING TIME OF WIND REPORTS FOR AVIATION

By M. J. O. DUTTON

Summary. For selected occasions during a 3-month winter period at London/Heathrow Airport, winds averaged over intervals of time from 30 seconds to 10 minutes were compared with the 30-second means at later times, simulating the procedure whereby wind observations provided by Air Traffic Control are used by a pilot; 30-second averaged winds logged by the digital anemograph logging equipment were used. The results are similar to those for an earlier study of summer situations at Heathrow: a 5–10-minute averaging period normally minimizes the root-mean-square error but the optimum periods for reducing errors exceeding various thresholds differ somewhat for threshold values of 12 knots or more; in general, the higher the threshold the shorter the averaging period necessary to minimize the frequency of departures exceeding that threshold. The few very large errors can be reduced by using a 30-second average at the expense of many more errors in the 6–14-knot range.

Introduction. The supply to aircraft pilots of a representative surface wind for take-off and particularly landing is an important feature in the safety of aircraft operations. This wind report is usually supplied to the pilot a few minutes before touchdown or take-off and in 1967 the International Civil Aviation Organization¹ (ICAO) provisionally recommended that a 2-minute average wind should be used until it had been shown to be inferior to a wind averaged over a different period. Sparks and Keddie² later showed that in a particular synoptic situation with strong westerly winds in a warm sector a 4–5-minute averaging period proved best for minimizing the root-mean-square (r.m.s.) differences between forecast and encountered winds. In a more recent study of turbulent occasions in a variety of synoptic situations during the summer of 1973 at London/Heathrow Airport, Hardy³ clearly illustrated the apparent dependence of the optimum averaging period on the relative importance of departures or errors of different magnitudes. His results showed that the few very large errors can be reduced by using a 30-second average (at the expense of more errors in the lower ranges) and that the r.m.s. error can normally be minimized by using a 5–6-minute averaging period; he concluded that a 2-minute average appeared to be a satisfactory compromise, but stressed that his results applied to summer in southern England and that the results for winter might differ. ICAO⁴ have since confirmed their recommendation of the use of a 2-minute average.

This note presents the results of an experiment designed to extend Hardy's work to winter-time at Heathrow, making use of winds logged by the digital anemograph logging equipment (DALE) operating in conjunction with a Meteorological Office Mk 5 wind system.⁵

Data for analysis. The DALE system, installed at Heathrow during December 1973, provided all the necessary data in the form of 30-second wind averages; it is a compact system with low power consumption which computes and records 30-second means of wind speed (to 0.1 knot), wind direction (to 1 degree), and maximum hourly gusts (speed to 1 knot, direction to 10 degrees). Wind speed is averaged instrumentally by electrical filter circuits before conversion to digital form; direction is converted to digital form at a 1-Hz sample rate before filtering.⁶ The system is constructed in such a way that the time constant can easily be changed to enable a different averaging period to be used. DALE writes recorded data in 1-hour blocks on tape in a cassette together with the time and maximum-gust information for that hour.

The cassettes are changed about once a month and the data transcribed on to magnetic tape. Initially the data contained many errors (mainly missing or invalid characters) but most of the problems in the initial trial period were quickly eliminated, although interruptions to the mains supply were a continual source of annoyance; to combat this problem the equipment was brought up to full operational standard with the inclusion of a stand-by battery in April 1974.

After necessary quality control the wind data covering the period 20 December 1973 to 25 March 1974 (total of 1775 hours with a few short gaps in the record) were processed by computer to produce various relevant wind statistics. Subjective examination of these statistics proved useful in selecting for analysis a total of 287 hours of 'turbulent' occasions. Initially the occasions selected included all periods with 10-minute mean wind speed greater than 15 knots, rapid changes of wind speed or direction or both, or reports of heavy showers or cumulonimbus clouds (total of 362 hours). In the final selection of the periods for analysis (47 periods totalling 287 hours) one of the main objects was to include all occasions when vector changes in the 30-second wind over periods of up to 20 minutes exceeded 10 knots. (In fact about 95 per cent of such occasions were included since, as already mentioned, there were several short gaps in the DALE data and two or three important periods were not logged.) Of the 287-hour sample, 81 per cent was selected from the January and February 1974 records alone; except for the last week or so of February this period was abnormally windy and mild in the United Kingdom.

Analysis. The object of the investigation was to compare, on a large number of occasions, the wind which might be supplied to the pilot with the wind which he would actually have encountered some minutes later at touchdown or take-off. The departure or error is defined as the magnitude of the vector difference between the forecast wind (reported wind assuming persistence) and the actual or encountered wind, the wind affecting the aircraft at or near touchdown or take-off. The forecast or reported wind was taken as the observed wind averaged over a period of time varying from 30 seconds to 10 minutes (simple arithmetic averaging of the 30-second winds was used) and the actual wind was taken as the 30-second wind average some time (lag) later; this lag, which represents the interval between the wind observation and the aircraft touchdown or take-off, was also varied from 30 seconds to 10 minutes. As Hardy pointed out, the 30-second run of wind past a stationary anemometer will usually be equivalent to the distance covered by an aircraft in a few seconds of flight and therefore represents eddy sizes of the correct order.

For all 47 sample periods totalling 287 hours the errors at every time-step, for 20 averaging periods and 20 lags, were evaluated and various statistics of these errors were computed; 916 minutes of data were lost in computing initial means and final lags so that in fact 271 hours and 43 minutes of 30-second wind data were used.

Results

Root-mean-square errors. Figure 1 shows the variation of r.m.s. error as a function of averaging period for various lags from 30 seconds to 10 minutes. The pecked lines join points on each curve corresponding to r.m.s. errors 1 per cent greater than the minimum value for each curve and indicate that,

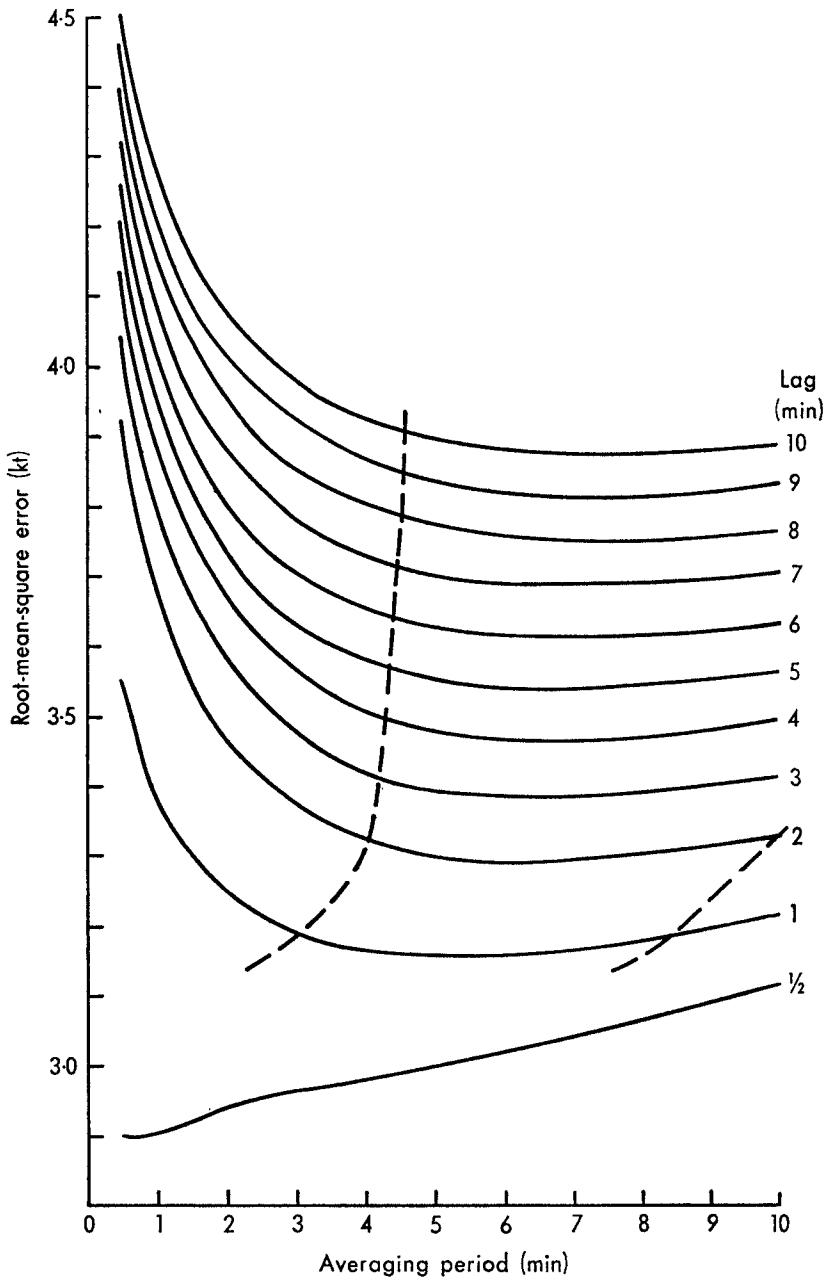


FIGURE 1—VARIATION OF ROOT-MEAN-SQUARE ERRORS WITH LAG AND AVERAGING PERIOD

The pecked lines join points on each curve corresponding to r.m.s. errors 1 per cent greater than the minimum value for each curve.

for a lag of 2 minutes or more, there is little to choose between averaging periods in the broad range of 5 to 10 minutes. It is obvious that for this range of averaging periods the r.m.s. error is much more sensitive to changes in lag than to changes in averaging period; for instance, a change in the latter from 7 minutes to 10 minutes at a lag of 5 minutes results in only a 0.6 per cent increase in r.m.s. error, whereas a change from a 5-minute to a 10-minute lag for a 7-minute averaging period produces a 9.3 per cent increase. For the shortest lag of $\frac{1}{2}$ minute, a $\frac{1}{2}$ -1-minute average is best.

Percentages of errors exceeding various thresholds. Figures 2, 3 and 4 show the variation with averaging period, for various lags, of percentages of errors (out of a total of 32 607) exceeding 6 knots, 10 knots and 14 knots respectively.

- (a) *6-knot threshold* (Figure 2). For all lags greater than $\frac{1}{2}$ minute the percentage of errors ≥ 6 knots is a maximum for the shortest averaging periods and can be minimized by using an averaging period of 5 to 10 minutes; for a $\frac{1}{2}$ -minute lag a $\frac{1}{2}$ -1-minute average is best. For lags of 2 minutes or more the number of errors ≥ 6 knots for a 2-minute averaging period (as recommended by ICAO) is 25-30 per cent greater than the number for a 5-10-minute averaging period.
- (b) *10-knot threshold* (Figure 3). For lags greater than 3 to 4 minutes the variation with averaging period of the percentage of errors exceeding 10 knots is similar to that for the 6-knot threshold; for the shorter lags Figure 3 shows that the optimum averaging period decreases from about 5 minutes for a 3-minute lag to 1 minute for a $\frac{1}{2}$ -minute lag. For lags of 3 minutes or more the number of errors exceeding 10 knots for a 2-minute averaging period is 22-27 per cent greater than the number resulting from the use of a 5-10-minute average.
- (c) *14-knot threshold* (Figure 4). Here the optimum averaging period appears to be about 3 to 6 minutes for lags of 5 minutes or longer and 1 to 2 minutes for the shorter lags.
- (d) *Higher thresholds.* The results for higher thresholds show that the higher the threshold the shorter the averaging period necessary to reduce the number of errors exceeding that threshold.

Table 1 lists percentage frequencies of errors exceeding thresholds of 6 knots, 10 knots, 14 knots and 20 knots for 2-minute and 5-minute averaging periods and lags of 2, 5 and 10 minutes. The table illustrates well the sensitivity of

TABLE 1—PERCENTAGE FREQUENCIES OF ERRORS EXCEEDING VARIOUS THRESHOLDS

Lag minutes	Threshold (kt)			
	6	10	14	20
<i>per cent</i>				
2-minute averaging period				
2	6.56	0.442	0.086	0.019
5	8.19 (1.25)	0.804 (1.82)	0.196 (2.28)	0.049 (2.58)
10	10.98 (1.67)	1.227 (2.78)	0.319 (3.71)	0.104 (5.47)
5-minute averaging period				
2	5.12	0.405	0.095	0.028
5	6.62 (1.29)	0.699 (1.73)	0.193 (2.03)	0.058 (2.07)
10	9.36 (1.83)	1.027 (2.53)	0.316 (3.32)	0.101 (3.60)

Figures in brackets are the percentages as proportions of the 2-minute lag values.

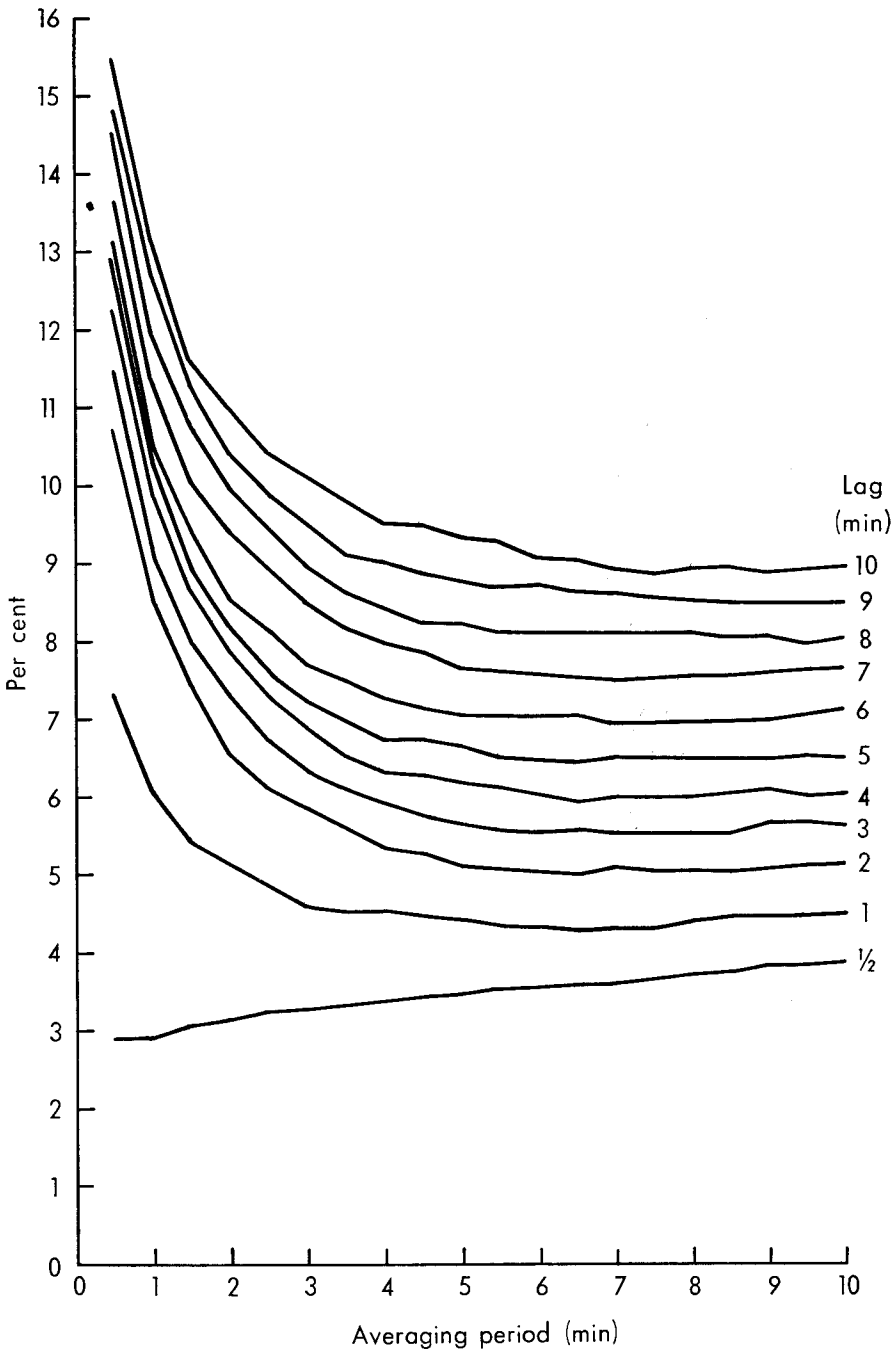


FIGURE 2—PERCENTAGES OF ERRORS ≥ 6 kt: VARIATION WITH LAG AND AVERAGING PERIOD

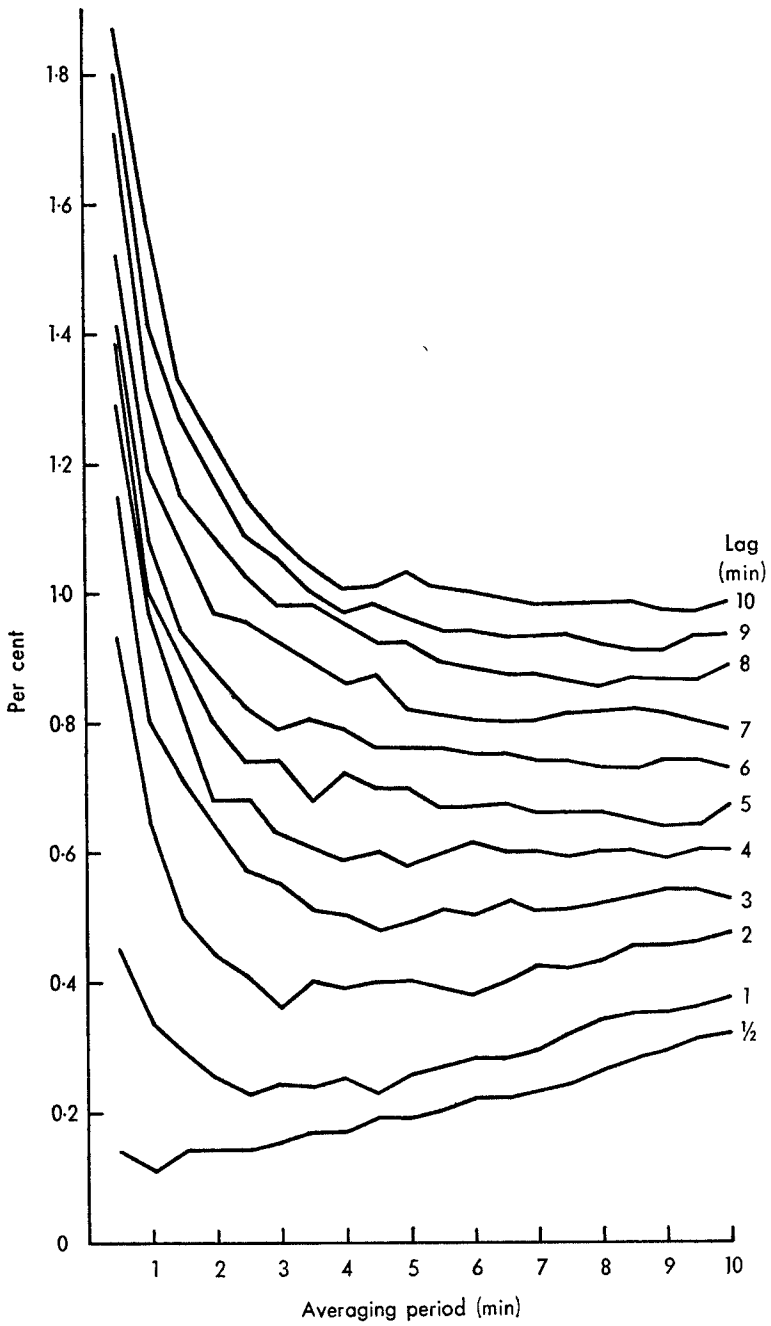


FIGURE 3—PERCENTAGES OF ERRORS ≥ 10 kt: VARIATION WITH LAG AND AVERAGING PERIOD

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PLATE I—ESSA 8 SATELLITE PICTURE AS RECEIVED BY AUTOMATIC PICTURE TRANSMISSION AT MASIRAH ON
20 OCTOBER 1972

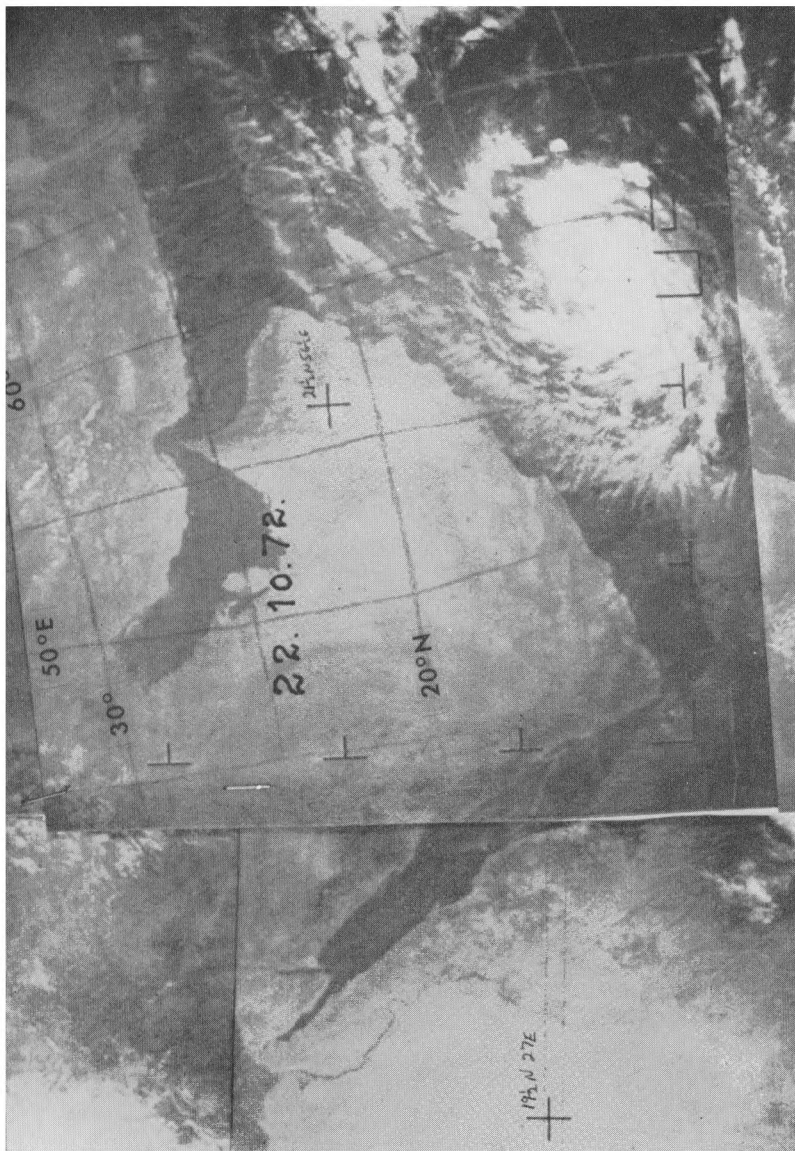


PLATE II—ESSA 8 SATELLITE PICTURE RECEIVED AT MASIRAH ON 22 OCTOBER 1972



PLATE III—ESSA 8 SATELLITE PICTURE RECEIVED AT MASRAH ON 24 OCTOBER 1972

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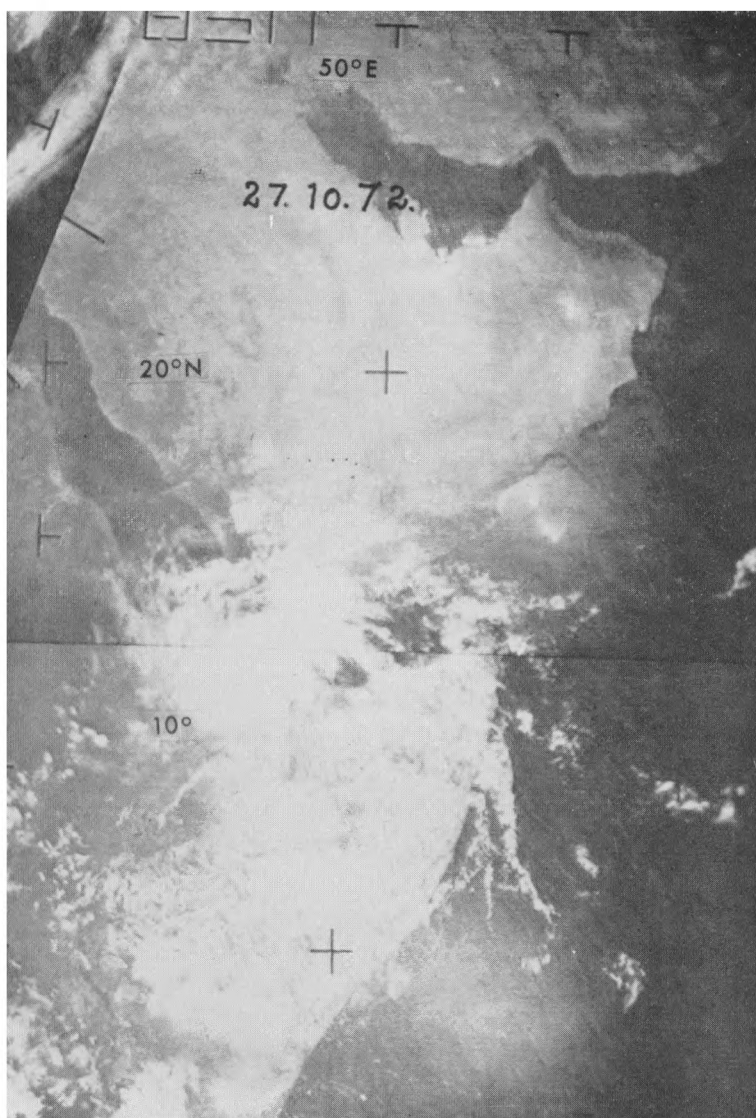


PLATE IV—ESSA 8 SATELLITE PICTURE RECEIVED AT MASIRAH ON 27 OCTOBER 1972

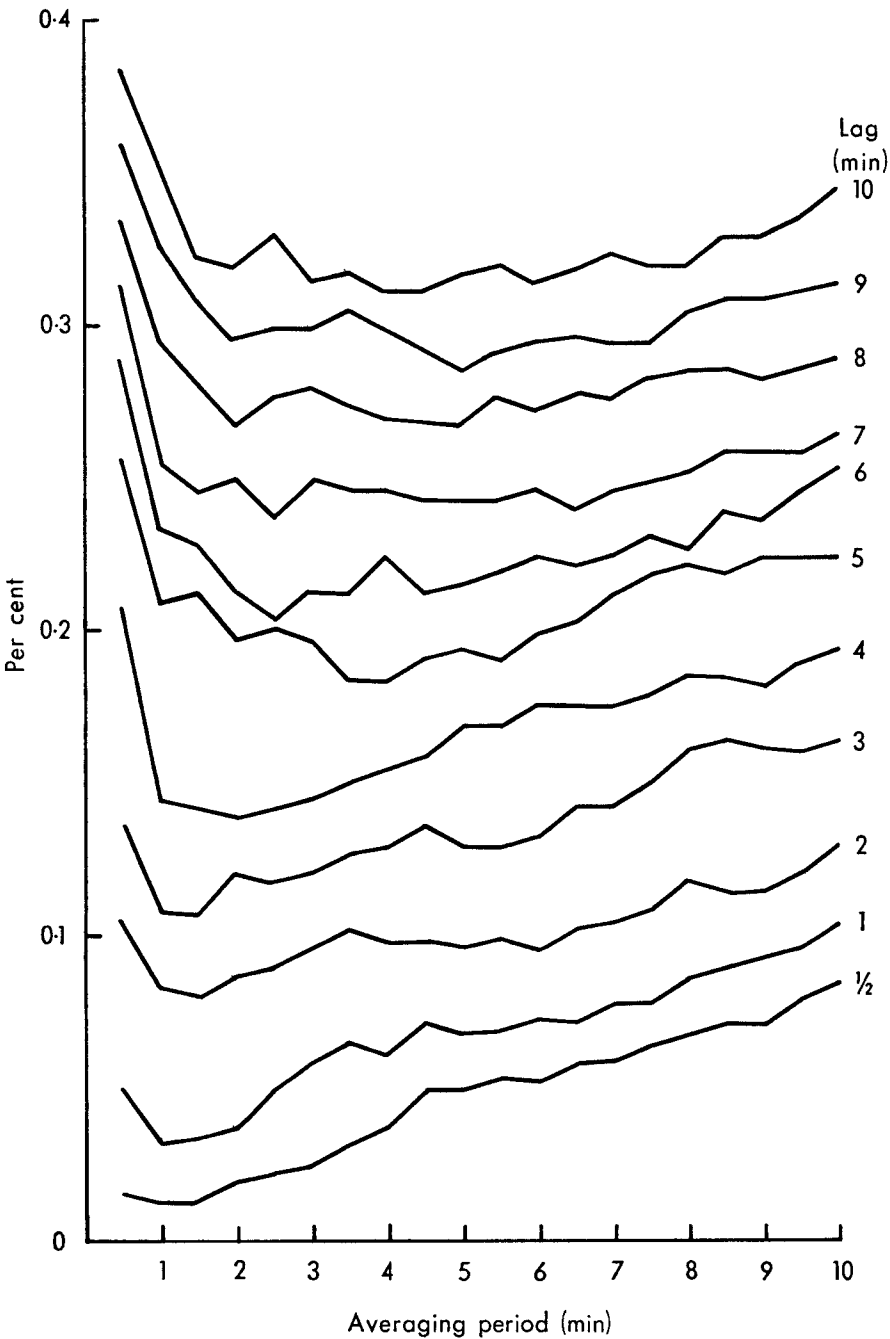


FIGURE 4—PERCENTAGES OF ERRORS ≥ 14 kt: VARIATION WITH LAG AND AVERAGING PERIOD

the figures to variations in lag and the increasing importance of as short a lag as possible as higher thresholds are considered. More than twice as many departures in excess of 14 knots occur with the use of a 5-minute lag as with a 2-minute lag for both averaging periods; if the lag is further increased to 10 minutes the frequency of these errors is over three times that for a 2-minute lag. At the 20-knot threshold the deterioration with lag is even more pronounced.

Discussion of results. The main difference between Hardy's summer results and those derived from this winter sample is that while the former suggested that, for all except the very short lags, errors exceeding 10 knots could be minimized by using a $1\frac{1}{2}$ -4-minute averaging period, the equivalent figures for winter show that a 5-10-minute average is best for lags of more than 3 to 4 minutes. In winter this averaging period also minimizes the r.m.s. error for lags greater than 1 minute; for summer, Hardy showed that a 5-6-minute average was best for minimizing the r.m.s. error.

The apparent discrepancy in the results for departures exceeding 10 knots is almost certainly due to the higher proportion, in the summer sample, of cases incorporating large and rapid wind-speed and direction changes. In a study of such 'events' at Bedford over a period of 4 years, Burnham and Colmer⁷ showed that they were normally associated with convective activity and occurred mainly in spring and late summer; on average only about 12 per cent occurred in the 4-month period November-February while more than half occurred in the 3-month period March-May. The winter sample was in contrast dominated by a high proportion of cases approximating to steady state in which the wind speed was generally high (with roughly constant direction) producing a high level of turbulence; there were relatively few cases where there was a large and rapid shift of wind direction and when these did occur, usually in association with the passage of active cold fronts or thunderstorms, they were accompanied by quite large increases in wind speed. Figure 5 includes four such typical cases; they are in fact the four occasions which produced the largest vector wind changes over 10 minutes or less in the winter sample. Most of the very large departures occur in non-stationary situations such as these and it is obvious that a short averaging period and, what is more important, a short lag are both desirable if their frequency of occurrence is to be reduced. On the other hand, in strong-wind steady-state conditions when fluctuations of the 30-second wind about a relatively stable long-period mean can be large, a longer averaging period is usually superior.

It is interesting to note that the variation with averaging period and lag of the percentage frequencies of errors exceeding 14 knots in the winter sample (Figure 4) is similar to that for the percentage frequencies of errors exceeding 10 knots in the summer sample. For minimizing errors below these thresholds (10 knots in summer, 14 knots in winter) it appears that a 5-minute or longer averaging period is superior to a shorter-period average, especially for lags of 2 minutes or more, whereas for minimizing errors exceeding the thresholds a $1\frac{1}{2}$ -4-minute average is best.

The results of this winter analysis indicate that the true overall occurrence frequency of departures in excess of 10 knots is about 0.1 per cent or 1 in 1000 for a 5-minute lag and 5-10-minute averaging period (about 1 in 800 for a 2-minute average). It should be remembered, however, that errors of this

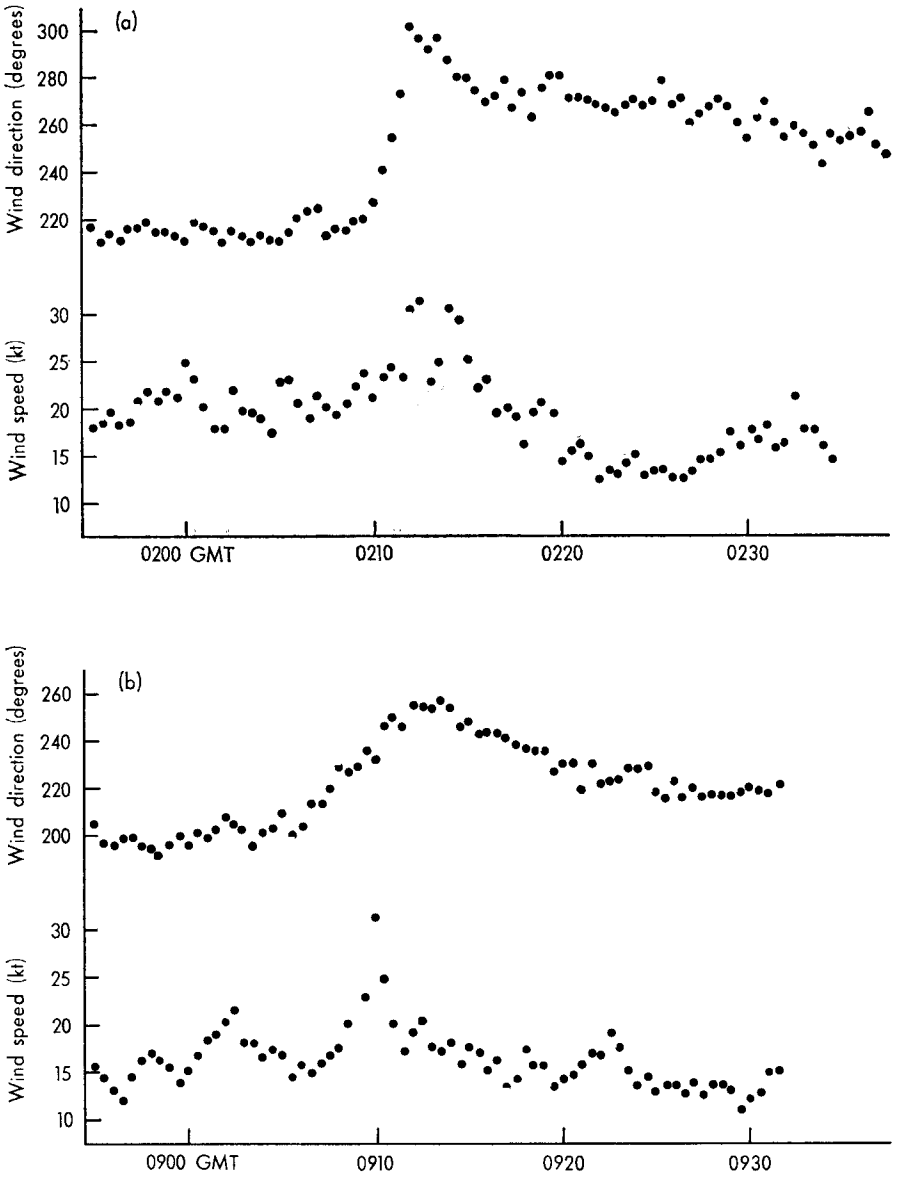


FIGURE 5—EXAMPLES OF LARGE, RAPID WIND CHANGES

(a) 11 January 1974 (b) 13 January 1974

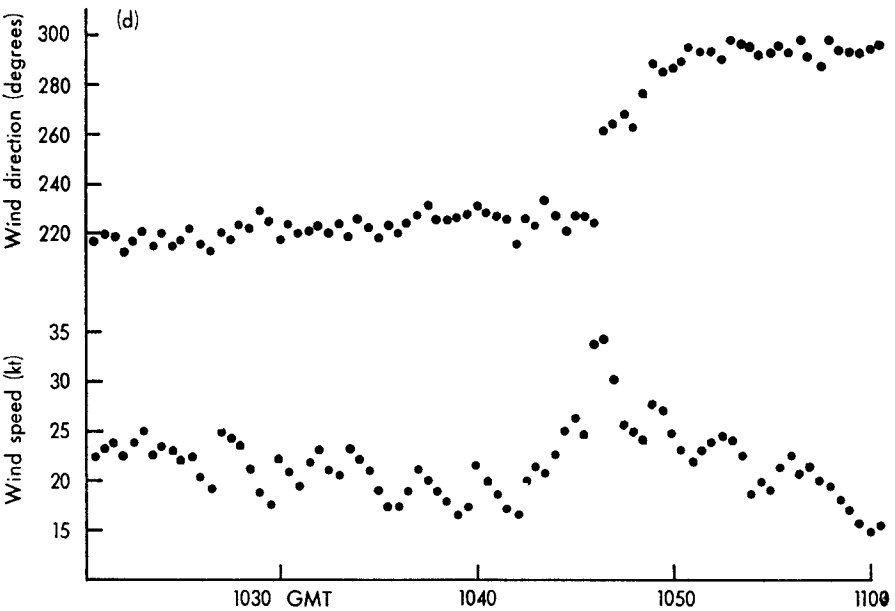
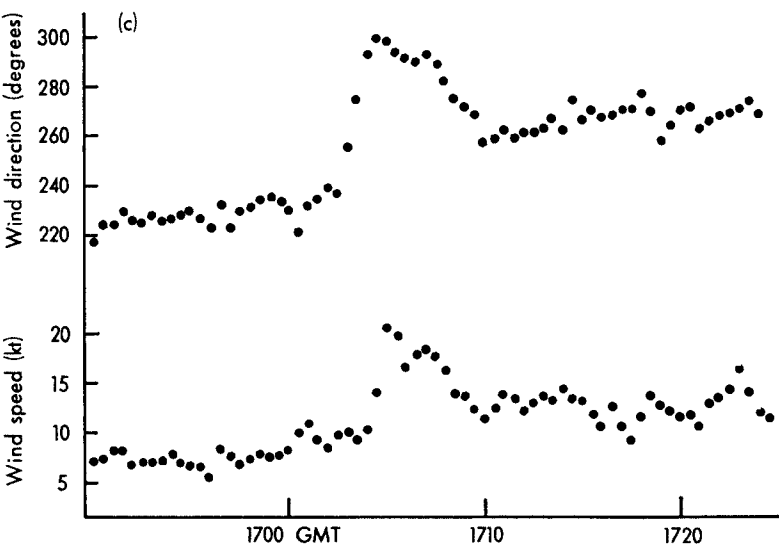


FIGURE 5—continued

(c) 2 February 1974 (d) 9 February 1974

magnitude and larger tend to occur in batches (i.e. occurrences are not entirely independent) and this tendency becomes increasingly pronounced as higher thresholds are considered.

This investigation and Hardy's study of summer situations has dealt only with the magnitude of the total vector departure and the question arises whether or not the results would be different for orthogonal components of the vector departure. The most obvious components to consider are those along (longitudinal) and across (lateral) the runway direction. The longitudinal component is usually more critical than the lateral component during landing and take-off.

Figure 6 shows some results of a limited pilot analysis (using two relatively small contrasting samples, for a 5-minute lag only) in which the total vector error was split into orthogonal components along and across the reported (forecast) wind direction. These components were chosen for the pilot study simply because the required data are contained in the winds themselves whereas an analysis of error components along and across the runway direction requires a knowledge of runway usage during the appropriate periods; there is no simple relationship between wind direction and runway selection at Heathrow.

The sample in case 1 is a single continuous 23-hour period in which the conditions approximated to steady state for much of the time; case 2 comprises six different periods totalling 32 hours which contain numerous large and rapid changes of wind direction or speed or both in mainly non-stationary conditions. The pecked and dotted lines in the figure represent the variations with averaging period of the percentage frequencies of error components exceeding 10 knots (components are along and across the direction of the forecast wind). The most interesting feature is that the variation in the frequency of large longitudinal errors is similar in the two cases, the frequency steadily decreasing with increasing averaging period. The percentage frequencies of large lateral errors are small for all averaging periods in case 1, but are appreciably larger in case 2 (exceeding the along-wind figures for averaging periods of 2 minutes or more) and increase with averaging period. So, on the basis of these two samples, it seems that an averaging period of 5 to 10 minutes minimizes the frequency of longitudinal errors in excess of 10 knots in most situations, but a short averaging period (less than 2 minutes) is apparently required to minimize the frequency of large lateral errors. However, the samples are small and this aspect of the optimum-averaging-period problem may require further study.

In this study, simulation of the aircraft landing and take-off situation has been attempted, but the method of simulation used is not entirely adequate, since only temporal variations of the wind have been examined, the reported or forecast wind and the actual wind some time later being compared at the same point. In the real operational set-up, unless the anemometer site happens to be near the take-off or touchdown point, the actual wind is experienced at a point which may be far removed from the anemometer. If accurate simulation is to be achieved, the appropriate spatial as well as temporal wind changes should be considered. Even if it can be assumed that the wind variations at one point are sufficiently representative of the required two-point differences, and this is probably a reasonable assumption for 30-second averages over homogeneous terrain and for a limited separation of the two points,

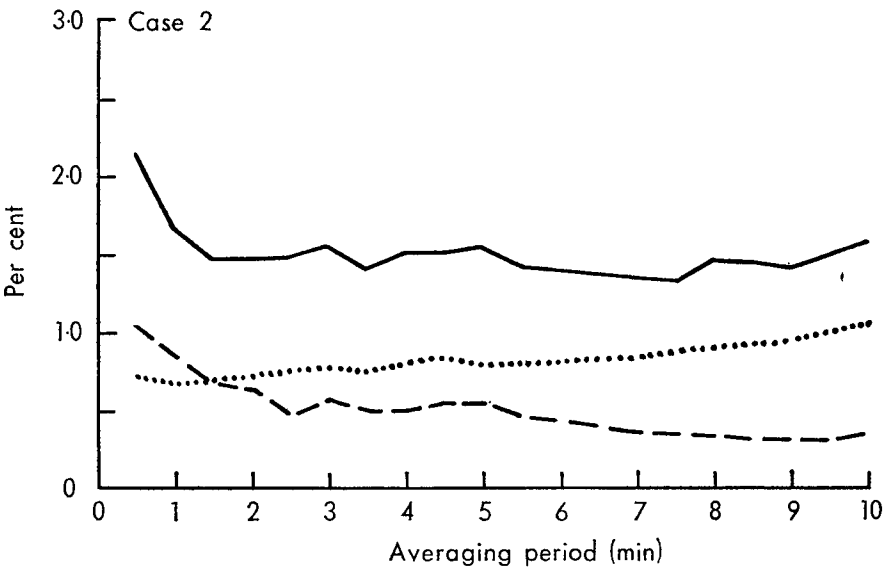
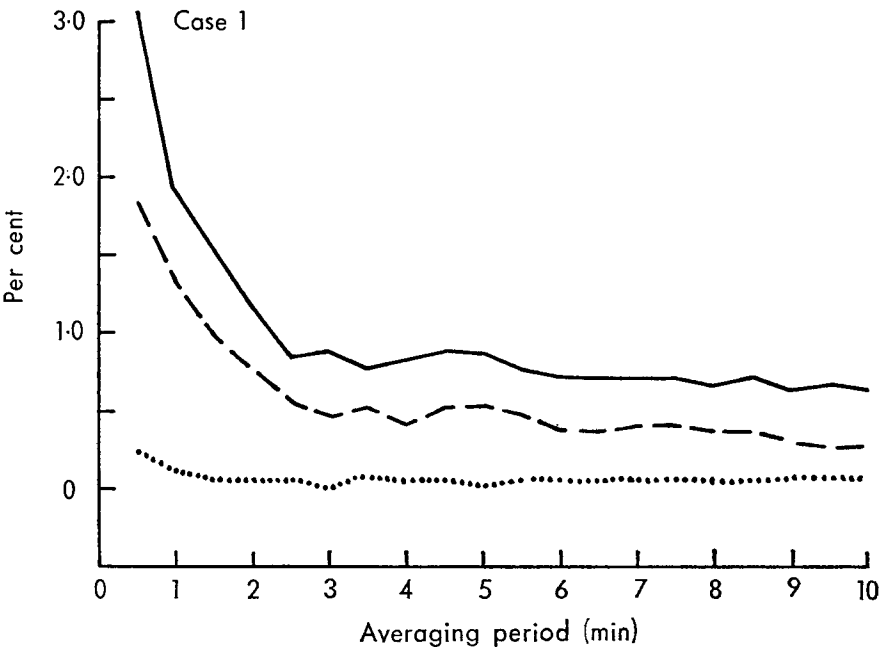


FIGURE 6—PERCENTAGES OF ERRORS ≥ 10 kt: VARIATION WITH AVERAGING PERIOD FOR 5-MINUTE LAG

—— Total error ---- Along-wind error component
 Across-wind error component

another important factor to bear in mind is that the effective lag is reduced if the anemometer is sited upwind of the touchdown point.

Summary of the main winter results. Analysis of 287 hours of winter 30-second wind records, logged by the DALE system at Heathrow, has shown that:

- (a) Differences between the reported mean wind and the actual encountered wind some time later can be most significantly reduced if the time lag between the wind observation and touchdown or take-off is reduced to a minimum.
- (b) A 5–10-minute averaging period minimizes the root-mean-square difference for all lags except the shortest ($\frac{1}{2}$ -minute) when a $\frac{1}{2}$ -1-minute average is best.
- (c) For lags greater than 3 or 4 minutes a 5–10-minute average minimizes the number of departures exceeding 10 knots; for the shorter lags a 1–4-minute average is best. In general the higher the threshold and the shorter the lag, the shorter the averaging period necessary to minimize the frequency of departures exceeding that threshold.
- (d) The ICAO-recommended 2-minute averaging period reduces the frequency of very large departures (greater than 15 knots or so), particularly for the shorter lags, but the resultant departures in excess of 10 knots are about 25 per cent more frequent than with a 5–10-minute averaging period if the lag is 3 minutes or more.

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ANNUAL DURATION OF ANY RAINFALL INTENSITY

By M. C. JACKSON

Summary. Several sources of data are discussed and results of their analysis are combined to produce rainfall-intensity statistics suitable for London and similar parts of the south and east of England. A composite graph showing the average fraction of total time during which any rainfall intensity is exceeded is derived from these statistics. A curve derived from similar sources for Eskdalemuir, Dumfriesshire is shown for comparison. It is suggested that the type of information given by these composite curves can be obtained for other parts of the United Kingdom, and that maps could be drawn for various intensities of rainfall.

Introduction. Information on the total time per year during which specified rainfall intensities are likely to be equalled or exceeded has long been sought by engineers, rainfall-sensitive industries and, particularly in the last few years, engineers concerned with propagation of radio signals through the free atmosphere. Harrold¹ has reviewed the present position and discussed the potential use of weather radar to derive attenuation statistics for radio signal propagation. Statistical estimates of rainfall intensity at a point have been made by Briggs,² and Briggs and Harker,³ who used the relationships with clock-hour rainfall totals. Recently further direct data have become available and these are used here in conjunction with data from other sources to produce estimates of the fraction of total time (i.e. fraction of the 'average' year) during which specified rainfall intensities are exceeded.

Analysing the data

Rainfall amount and duration tabulations. Hourly values of rainfall amount and duration at London/Heathrow Airport from the Dines tilting-siphon rain-gauge have been recorded on Meteorological Office Metform 3440 and are now stored on magnetic tape for virtually the whole of 23 years. Recently Hardy (private communication, 1974) has analysed these data to produce the total duration of rainfall between various values. From these data the average duration, expressed as a fraction of total time, can be estimated for rainfall intensities greater than (or equal to) any given value. However, tabulations on Metform 3440 are never made to a greater precision than 0.1 hour, so that the durations of short, rare events are inevitably underestimated.

For several stations in the United Kingdom the average annual duration of intensity greater than or equal to 0.1 millimetre per hour was compared with the 1941-50 average rainfall duration given in *British Rainfall* 1957,⁴ and found to be quite similar, with approximately 450 hours per year for stations in the London region (a fraction of total time equal to 5×10^{-2}) but with large differences between individual station values. The data for Kew, 1956-71, derived directly from Metform 3440 gave durations which were more than 10 per cent greater than those given in *British Rainfall*. Such discrepancies may be expected for low rainfall intensities, bearing in mind the differences between the frictional characteristics of various rain-recorders, and are not considered further in this paper.

Rapid-response rain-gauge tabulations. Other sources of data were investigated, and data from one year's operation of the rapid-response rain-gauge at the Radio and Space Research Station (RSRS) at Slough as presented by Norbury *et alii*⁵ were used to extend information for a wide range of rainfall intensities above about 3 mm/h occupying fractions of total time of less than 5×10^{-3} (about 40 hours per year). Results were very close to those obtained from tabulations on Metform 3440 from readings taken at London/Heathrow Airport which gave, for the same lower limit of intensity, a fraction near 5×10^{-3} , and very close to the results obtained by Evans (private communication, 1974) from the rapid-response rain-gauge at Colchester (University of Essex) for intensities occupying fractions of total time between 10^{-3} and 10^{-4} .

The RSRS equipment counts the average rainfall intensity over 10-second intervals through the year and records the clock time by a data-logging system with a paper-tape output, so that a count of total duration above any specified

intensity can be made. It is described more fully by Norbury and White.⁶ Further data are being produced for subsequent years.

The use of only one year's data raised the question of their representativeness, especially for very short durations. Durations calculated from Jardi rate-of-rainfall tabulations for Kew between 1934 and 1943, for intensities equal to or greater than 10 mm/h, show that the coefficient of variation (the standard deviation divided by the mean) of annual durations is rather more than 10 per cent; this coefficient will become even greater at shorter durations (and higher intensities). However, the values from the rapid-response rain-gauge are probably the best estimates of the true mean values that are available for fractions between 10^{-3} and 10^{-5} .

Jardi rate-of-rainfall recorder tabulations. The Jardi rate-of-rainfall recorder⁷ measures rainfall intensities instantaneously (in practice it has been estimated to average over 15-second intervals), and four or five such instruments have been in operation at different places in the United Kingdom. One of them was operating fairly continuously at Kew Observatory for many years, and tabulations for 10 years from 1934 to 1943 were analysed to obtain the fraction of total time with intensities greater than 10 mm/h. This fraction (6.8×10^{-4}) was found to agree quite closely with that from the rapid-response rain-gauge (5.3×10^{-4}) at an intensity of more than 10 mm/h.

It was found from Jardi tabulations that an intensity of more than 50 mm/h occurred on average 15.3 times per year on a total of 8.6 days (Table I). If this is combined with a fraction of total time (from the rapid-response rain-gauge for 1970) equal to 5.3×10^{-5} (or approximately 30 minutes per year), a rainfall event* of intensity more than 50 mm/h is suggested to last, on average, about 110 seconds. From this duration it is tentatively suggested that rainfall events of intensity greater than 75, 100 and 150 mm/h would have average durations of about 90, 75 and 50 seconds (i.e. reducing slowly with increasing intensity, but remaining of the same order of magnitude).

TABLE I — ESTIMATES FROM JARDI DATA, OF FRACTIONS OF TOTAL TIME DURING WHICH THE GIVEN RAINFALL INTENSITIES ARE EXCEEDED

Rainfall intensity exceeded mm/h	Days per year	Events per year	Average duration of event s	Fraction of total time
50	8.61	15.3	109	5.3×10^{-5}
75	3.70	(6.5)	(90)	(1.9×10^{-5})
100	1.65	(2.8)	(75)	(6.7×10^{-6})
150	0.26	(0.4)	(50)	(6.3×10^{-7})

Estimated values are in brackets.

The ratio of the number of days to the number of events with rainfall intensity more than 50 mm/h is 1.77. This value should stay fairly constant or reduce only very slowly with more intense rainfall events, and the value was used with the average annual number of days with intensities greater than 75, 100 and 150 mm/h to produce tentative estimates of the average number of events per year. The estimates of the average number of events per year (column 3 in Table I) and the average duration of the event (column 4 in Table I) help to make possible a tentative extension of the graph down to a fraction of total time

* 'Rainfall event' is here defined to mean a continuous period of rainfall with mean intensity greater than some specified value.

equal to 6×10^{-7} (approximately 20 seconds per year). It was encouraging that estimates of intensity for these very small fractional durations agreed well with those obtained directly from a very small quantity of data from the rapid-response rain-gauge.

The diagram. Results from the various data sources described in the previous section were plotted on one diagram (Figure 1). The range of intensities and durations is so large that log-log graph paper is essential. The final composite curve, shown as a full line in Figure 2, was obtained by inspection and subjective smoothing of the data, the higher-intensity values from London/Heathrow Airport and the lower-intensity values at the University of Essex being ignored, and represents London or somewhere with similar rainfall in south and east England. Table II presents some of the estimates derived from Figure 2 for specified rainfall intensities, both in fractional and actual durations.

TABLE II — ESTIMATES OF AVERAGE FRACTION OF TOTAL TIME DURING WHICH GIVEN RAINFALL INTENSITIES ARE EXCEEDED IN THE LONDON REGION

Rainfall intensity exceeded <i>mm/h</i>	Actual duration in an 'average' year	Fraction of total time
0.1	440 h	5.0×10^{-2}
0.5	320 h	3.7×10^{-2}
1.0	220 h	2.5×10^{-2}
4	28 h	3.2×10^{-3}
10	4 h 40 min	5.3×10^{-4}
25	1 h 15 min	1.4×10^{-4}
100	3½ min	6.7×10^{-6}

For contrast, a similar analysis for Eskdalemuir, Dumfriesshire (altitude 242 m, 1916–50 average annual rainfall 1580 mm, average annual duration of rainfall 1200 hours) was derived from autographic rainfall-recorder and Jardi rate-of-rainfall recorder tabulations, and added to Figure 2 (dashed curve). The average annual rainfall and the average duration of all rainfall at Eskdalemuir are both about two-and-a-half times typical values for south-east England.

Discussion. The parts of the composite curves in which the author is most confident are those between fractions of the year of 10^{-2} and 10^{-4} . At low rainfall intensities more elaborate equipment is needed to indicate when the intensities go below or above a certain value. For the high-intensity-short-duration part of the diagram, where there is most interest, many more data are needed, covering several years, from equipment which can accurately record all 'cloud-burst' rain.

Similar curves for other parts of the country would be obtained if relationships were to be derived between rainfall parameters as described in this paper and rainfall parameters for rare rainfall events such as those given in the Flood Studies Report.⁸ The extension of the work is possible since rainfall tabulations are available for analysis from some 25 stations in the United Kingdom, and the Flood Studies Report contains methods of obtaining detailed mapping of relevant rainfall parameters for uncommon events.

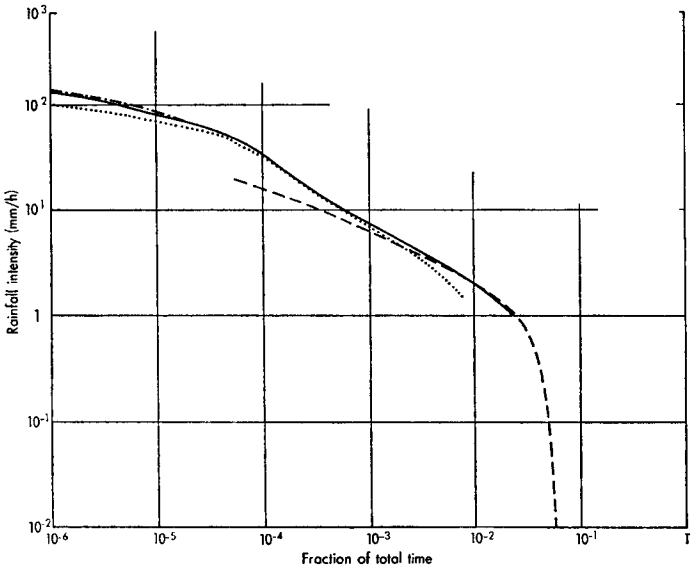


FIGURE 1—FRACTION OF TOTAL TIME IN WHICH SPECIFIED RAINFALL INTENSITIES ARE EXCEEDED

- Rapid-response rain-gauge at Slough
- Rapid-response rain-gauge at Colchester
- Hourly rainfall tabulations at London/Heathrow Airport
- .-.- Jardi rate-of-rainfall recorder at Kew

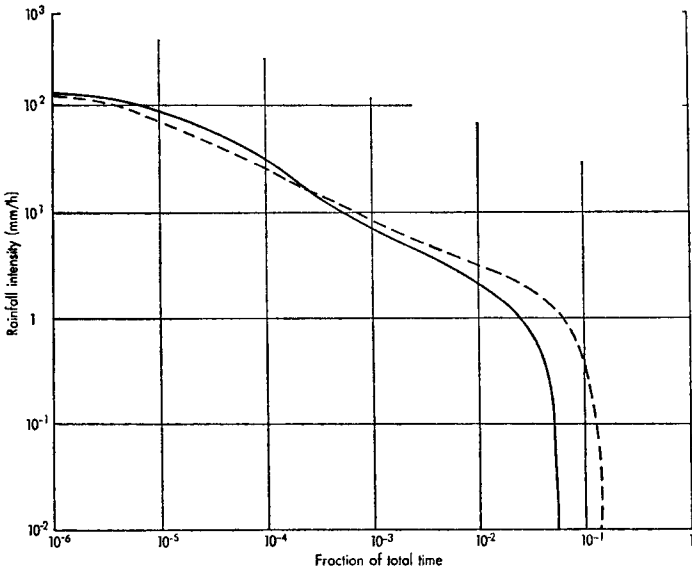


FIGURE 2—FRACTION OF TOTAL TIME IN WHICH SPECIFIED RAINFALL INTENSITIES ARE EXCEEDED

- Derived from data sources in Figure 1 for the London region
- Curve for Eskdalemuir, Dumfriesshire, shown for comparison

Conclusion. Figure 2 was drawn from tabulations of rainfall amounts and durations at London/Heathrow Airport, direct counts by rapid-response rain-gauges at the Radio and Space Research Station at Slough and at the University of Essex at Colchester, and tabulations from the Jardi rate-of-rainfall recorder at Kew. With these data the composite curve of fraction of total time against intensity was extended down to fractions of total time equal to 10^{-6} . A curve derived in a similar manner for Eskdalemuir in the southern uplands of Scotland is added to show the contrast for a significantly rainier place. Until new and more plentiful observations become available, the main composite curve in Figure 2 should be of use to the many inquirers for estimates of this kind, especially in south and east England, and could lead to the production of estimates for other parts of the United Kingdom.

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REVIEW

New Science in the solar system, edited by P. Stubbs. 300 mm × 210 mm, pp. 65, illus., New Science Publications, 128 Long Acre, London WC2E 9QH, 1975. Price: £1.

This little book (or large pamphlet) contains 13 articles which together give a fairly comprehensive account, in quite simple terms, of current knowledge of and ideas about the planets. The contents comprise: 'Cosmogony Now' (John Darius), 'The Sun from Skylab' (John Eddy), 'Mercury' (John Guest), 'Venus' (Garry Hunt), 'Earth' (Peter Stubbs), 'Moon' (Thomas Gold), 'Mars' (Harold Masursky), 'Weather on the Inner Planets' (Richard Goody), 'Jupiter' (Garry Hunt), 'Saturn and Beyond' (Simon Mitton), 'The Debris' (Keith Hindley), 'Future Missions' (Garry Hunt) and 'Exobiology' (Carl Sagan). It can be seen that the contributions carry authority, although occasionally carried away by enthusiasm in such extravagant phrases as 'a milestone in space exploration, and more than an epoch in solar physics'. The casual reader will immediately be impressed by the range and quality of the photographs and diagrams, for the most part drawn from NASA material. Many people will find it worth while to

have this book for its varied and valuable photographs and diagrams alone. I have one main criticism. The value of the book is seriously, indeed damagingly reduced, by the absence of references. I find this inexcusable. A few key references, such as the account of the MARINER 10 and PIONEER 10 results in *Science*, of the lunar seismic results, of the Moon's gravity field, of plate tectonics, and so on—just one or two items in each article, would have made the book an excellent starting point for studying recent work more thoroughly; as it is, its value to the serious student is very little. A minor criticism is that the proofs have been carelessly read—there are a number of annoying and rather trivial misprints.

This is no place, nor is it the time, to write a comprehensive review of our knowledge of the solar system. 'The Solar System' does however call to one's attention the number of illuminating comparisons that it is now possible to make between various bodies in the solar system.

We know the size, mass and density of all planets and most satellites; for most, with the principal exception of Pluto, the uncertainties are relatively low. We know the moments of inertia for many (Mercury, Venus and Pluto are the principal exceptions) and so we have an idea of central condensation of mass and the likelihood of a core. The Moon must have a nearly uniform density, about the same as the mantle of the Earth, Mars is little condensed, Jupiter and Saturn very strongly condensed. In view of the relatively high mean densities of Mercury and Venus it is unfortunate that we have no indication from the moments of inertia as to how much the density may increase with depth. We have seismic information only about the Moon, but the picture is intriguingly different from that of the Earth. We know that the rate of heat flow per unit area from the Moon is about half that from the Earth; we also know that heat flows out of Jupiter. The Earth and Jupiter have strong magnetic fields; Mercury has an appreciable one, while the Moon, Mars and Venus have very small fields, probably of complex structure. The Earth, Venus, Jupiter and the satellite Io have atmospheres with ionospheres controlled by the height of maximum absorption of solar radiation; the Earth, Jupiter and Mercury have magnetospheres in equilibrium between the magnetic field of the planet and the field convected by the solar wind. Finally, the appearances of the surfaces of the Moon, Mars and Mercury, being unshielded by atmospheres, are dominated by craters formed by impacts of meteorites, while the Earth, the Moon, Mars and Mercury all appear to be asymmetrical, two hemispheres of different appearance being distinguishable. Such comparisons are stimulating alike to theory and to observation; one virtue of 'The Solar System' is that it calls them to our attention.

A. H. COOK

LETTER TO THE EDITOR

551.509.334:551.583.1

Reflections upon some unusual years

An article¹ in the *Meteorological Magazine* for March 1975, referring to some of my earlier work on the rainfall of the British Isles, prompts me to make the following comments.

On page 66 the authors state that monthly values for England and Wales were published in the *Meteorological Magazine* for 1928, but this article gave only the annual values, the monthly values being published later.² The uncertainty of the values for the earlier years was explained in both these articles.

One reason for this work was that I had noted some necessary revisions to the earlier published annual values by Symons. This revision involved much preliminary work, including the preparation of annual³ and decadal⁴ maps. I had always hoped that before retiring it would have been possible for me to go over this work using the 'ancient records' which were being accumulated by the Meteorological Office. In the further examination of these earlier records, which now seems overdue, I hope that this cartographical approach will be combined with statistical analysis.

On pages 66 and 67 the authors do not mention that the rainfall distribution over the country has been defined and published for many years, including the wet 1872 and the dry 1887.³

On page 68 the authors conclude that since 1727 both 1768 and 1852 rival 1872 in being very wet over a large part of the country. This is not a new idea since in the 1928 article on 'Two centuries of rain' there is a similar statement that 'the three years 1768, 1852 and 1872 were markedly wetter than 1927'.

On page 62 the authors compare Lamb's Daily Weather Types with the annual rainfall in extreme years. It may be worth recording that earlier⁵ a comparison was made for each of the years 1868-1921 of the rainfall in the west, east, south and north of the country with the annual pressure and the pressure gradients south-north and west-east. This paper gives some interesting results which might warrant further study.

On page 65 the authors state that in the discussion of Reynolds's paper no mention was made of the unique position of Bidston in the rain-shadow of Snowdonia. This is fully explained in the first page of Reynolds's paper and those who discussed the paper realized that this could not account for the wetness of 1872 there. In the first place, percentages of annual averages are locally almost independent of the orography; then the percentage map for 1872 showed seven other areas, well distributed over the country from the east coast to the Cheshire Plain with 170 per cent of average, as recorded in the Bidston area. Clearly the similar rainfall of all these eight areas could not be due to similar rain-shadow effects.

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J. GLASSPOOLE

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Reply by Mr J. M. Craddock:

The main purpose of our paper is to find better arguments for answering questions such as 'What is the statistical probability of another year as wet as, or wetter than, 1872?' I am glad Dr Glasspoole has been able to contribute to the discussion and I would only make the following points:

(a) Dr Glasspoole writes 'percentages of annual rainfall averages are locally almost independent of orography'. I would be inclined to add 'provided that the mixture of weather types during the year is not too far from the average'. The question of using the percentage observed at one station to estimate that at another is important in any attempt to homogenize long-period rainfall records, and I would ask Dr Glasspoole whether he knows of any work which puts figures to the relationship, and limits to the residual error. His paper with Mr Salter¹ goes part of the way, but more is needed if we are to make the best of the earliest records.

(b) My latest provisional calculations of the percentage annual rainfall totals in 1872 for individual stations in 11 districts, where there percentages are based on averages over all available years for each station, give the following values:

Exeter 148.5; Ross-on-Wye 131.8; Oxford 113.5; London 134.3; Thwaite, Suffolk 119.7; Pode Hole, Lincs. 133.1; Mickleover, Derbys. 145.8; Leeds 154.1; Liverpool, Bidston 159.8; Kendal 137.3; and Carlisle 120.0. My figure of 159.8 for Liverpool, Bidston is based on a normal of 28.58 in, the actual average there for the 103 years, 1867-1969, and agrees with the 159 per cent given by Reynolds.² Incidentally, this is the third highest of 1584 such values which I have found for the 11 areas for each year from 1830 to 1973, and suggests that the probability of the annual rainfall total at one station exceeding 160 per cent of the normal there is about 1/528. The 11-area average for 1872 is about 136 per cent, the highest for any year from 1725 to 1973 compared with the figure of 144 per cent given by Dr Glasspoole in his 1928 paper.³

(c) It is true that Reynolds² refers to Bidston as being in the shadow of Snowdonia, although Doodson and Bigelstone⁴ and Zoch⁵ do not seem to have realized its relevance, but the point we were trying to make is that 1872 was a year in which the days when Bidston received the benefit of this protection were much fewer than usual, whereas the days in which the rain came from other directions were more numerous. Thus Bidston should be outstandingly wet in what was in any case an extremely wet year, and this is just what is shown by the above figures for the 11 districts.

(d) Dr Glasspoole will be pleased to know that I hope to continue to work on this subject, using both statistical and cartographic methods, when I join him in retirement. I think, however, that it is most important in these days of electronic computers, to quote the original data worked on wherever possible. The scope for computerized analysis is so great, compared with earlier methods, that a new experiment is always liable to cast doubt on some previous results, which then have to be tracked back to source.

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NOTES AND NEWS

Symposium on Weather Radar and Water Management

A symposium with the above title will be held from 15 to 18 December 1975 under the auspices of the Water Research Centre and the Royal Radar Establishment (RRE). It will be based at the Grosvenor Hotel, Chester, and will include field visits in North Wales and a visit to RRE at Malvern.

The symposium will report the use of radar for rainfall measurement, real-time applications of radar derived data and the importance of radar networks to rainfall forecasting. The work described arises out of the Meteorological Office/RRE Weather Radar Network Project, the Dee Weather Radar Project and the Dee Hydrological Forecasting Project. Organizations involved in these projects include the Central Water Planning Unit, Institute of Hydrology, Meteorological Office, Plessey Radar Ltd, Royal Radar Establishment, Water Data Unit of the Department of the Environment, Water Research Centre, and the Welsh National Water Development Authority.

Speakers from the Meteorological Office will include Dr T. W. Harrold and Mr C. G. Collier.

Further information may be obtained from Mr C. F. Cooper (on attendance) or from Mr J. A. Cole (on technical contributions) at

Water Research Centre,
Medmenham Laboratory,
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Medmenham,
Marlow,
Buckinghamshire SL7 2HD,
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Cables: Water, Marlow.

OBITUARY

It is with regret that we have to record the death of Mr A. W. Carmichael, Higher Scientific Officer, Glasgow Airport, on 20 April 1975.

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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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OBSERVATION AND ANALYSIS OF AN ICE HYDROMETEOR OF EXTRAORDINARY SIZE

By R. F. GRIFFITHS*

(Physics Department, University of Manchester Institute of Science and Technology)

Summary. A fragment of a very large hydrometeor was analysed in the laboratory where standard thin-section techniques were used to reveal its structure. The ice fell at the time of a severe lightning stroke which occurred in Manchester on 2 April 1973, a day when heavy rainfall was recorded in the area. Inquiries have revealed the pattern of nearby aircraft movements at the time, and it is suggested that the lightning was triggered off by an aeroplane which flew into the storm. No definite conclusion as to the origin of the sample has been arrived at, except that it was composed of cloud water.

Introduction. The unusual meteorological conditions that occurred over the United Kingdom on Monday, 2 April 1973, caused widespread gales and heavy precipitation in many districts. The Coastguard station at Whitby, in Yorkshire, reported gusts of 110 mile/h, and shipping movements on the Mersey were suspended for part of the day owing to poor visibility. Gale-force winds and heavy rainfall were also recorded in southern districts. Manchester experienced a moderate snowfall in the morning, and this gave way to clearer skies in the afternoon. Shortly after sunset, cloud began to form and at 1900 GMT the cover was 3/8 cumulus with the base at 600 m.

At 1954 GMT a single flash of lightning occurred which extended over a very wide area of Manchester. This was noted by many people because of its severity, and because there were no further flashes. The Manchester Weather Centre recorded the lightning, which took a path at least 10 km long from Cheadle in the south to the city centre, and may have gone farther. A fall of hail in Wilmslow was observed at around the same time and there may well have been others. At the time of the stroke the author was walking along Burton Road, Manchester, near Withington Hospital, and, in his capacity as a lightning observer for the Electrical Research Association, he made a note of the time and nature of the flash as well as of the prevailing weather. The estimated interval between the flash and the thunder was two to three seconds, which suggested a lightning channel about 800 m away and, relative to the height of the cloudbase, almost directly overhead. No precipitation was

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observed at this stage. As the author returned a few minutes later by the same route, a large object struck the roadway about three metres to his left front, precisely at the junction of Burton Road with Bottesford Avenue (National Grid reference SJ 839922). This object fell fast enough to be shattered into many pieces on impact with the ground; only one fragment of any appreciable size could be found, the rest being scattered in tiny pieces over an area of many square metres. The time at which this object struck the ground was noted as 2003 GMT. On inspection, the fragments proved to be made of ice, and the large piece, when held up to the street light, showed rings of clear ice alternating with rings of bubbles trapped in the structure. Anxious to preserve this fragment so that it could be inspected in the laboratory, the author immediately ran home and was able to stow it in the freezing compartment of a domestic refrigerator in less than 10 minutes, with only minimal loss from melting. A light fall of sleet followed, lasting about 10 minutes. The air temperature was measured at this time, and was found to be 3°C; there was a just discernible breeze, which was too light for its direction to be fixed. The fragment was transferred to a cold room and a number of tests and experiments were performed on it in the hope that the results would throw some light on its probable origin.

Tests carried out on the fragment. As soon as possible after the ice was transferred to the laboratory, measurements of various kinds were made on the whole fragment, and photographs were taken to record its size and shape before the performance of any tests that would necessitate breaking the piece into smaller sections. The fragment weighed 612 g and was 14 cm in its longest dimension. The view seen in Plate I shows the layered structure of the whole piece. The centre of growth is missing, but it is evident from the disposition of the layers that the nucleus was somewhere in the region of the bottom left-hand corner as seen in the photograph, since the growth layer surfaces have an apparent centre at that point. The front of the sample in this photograph lies roughly in the plane of the apparent centre, and the outer layer, which is on the top and right sides, extends round to the back. The form of the layers shows that the original whole piece had roughly spherical symmetry, although distortion in this respect is introduced owing to the clear existence of a preferred direction of growth. It was decided to apply the techniques of structural analysis that are commonly used on hailstones. These involve the photography of thin sections of the ice sample in ordinary reflected or transmitted light, and also with the sections in various orientations between crossed polaroids. The former technique reveals the distribution of bubbles in the ice, and the latter shows the size and orientation of the crystallites; the crossed polaroid photographs are particularly effective if taken in colour, although black-and-white will often suffice. These photographs can then be used to extract information about the probable characteristics of the stages of growth in the ice specimen. Such methods have been used by many people and are described by List.¹

In the process of preparing the sections it was possible to obtain samples of the melt water from successive layers of the fragment. The pH of this water was measured and all samples lay within the range 6.0 to 6.5, which is slightly basic relative to equilibrium with carbon dioxide at about 5.6 to 5.8 pH. The conductivity, σ , of the melt water was measured at 20°C and was found to

be 4.9 millisiemens per metre (mS/m), a value close to that measured for a sample of overnight rainwater (collected some time later in the same area) of 4 mS/m, supporting the view that the ice sample was composed of cloud water. By way of comparison, σ for tap water and laboratory-distilled water samples was found to be 20 mS/m and 0.3 mS/m respectively.

Preparation and photography of the thin sections. The sections were prepared and photographed in a cold room in which the temperature was maintained at -15°C . The ice sample was cut into six slices each about 0.5 mm thick which were then mounted on glass slides. The specifications of the six sections are given in Table I. The specimens were then placed in turn on a universal stage and photographed in black-and-white with transmitted light, and then in colour between crossed polaroid sheets.

TABLE I—SPECIFICATIONS OF SECTIONS

Section number	Shown in Plate	Plane	Location
1	II	Tangential	Parallel to section 2, 3 cm from the principal axis of growth
2	III, VI and VII	Radial	On the principal axis of growth
3	IV and VIII	Radial	Perpendicular to section 2; includes part of the polar surface layer at the smaller end
4	not shown	Tangential	Through the equatorial surface layer
5	V	Radial	Through the polar surface layer
6	VIII	Radial	Adjacent to section 3, showing a region intermediate between the centre and the surface

Note. A radial plane is any plane passing through the centre of a spheroid; a tangential plane is any plane that is not radial and is at some point tangential to one of the bubble-line surfaces. The polar region is at the end of the major axis and the equatorial region is at the end of the minor axis.

Interpretation of the photographs. Without making any assumptions about the origin of the ice fragment, the application of hailstone analysis techniques would appear to be the obvious approach in this case. Browning² presents a summary of the considerations involved in such work.

The fragment was found to have 51 layers of clear ice separated by thinner layers of trapped air bubbles. These features are clearly seen on the two large sections, 1 and 2, shown in Plates II and III respectively. The remains of the closest ring of bubbles to the centre can just be seen in Plate VII at the edge of the section before the first clear partial ring. The major and minor axes are taken to be those two directions, perpendicular to each other, in which the growth rates appear to be respectively greatest and least. A preferred direction of growth is indicated by the greater thickness of the rings of clear ice in the direction of the longer axis. The ratio of the semi-axes was 0.62 and this ratio is preserved in each growth layer of transparent ice. In the nomenclature adopted here, the centre is at the lower left of the bubble photograph of Plate II, the equatorial region is at the top left, and the polar region is at the bottom right. This terminology will be used throughout to identify the parts referred to. Diameters of the bubbles range from 0.1 to 0.5 mm, with a predominance at 0.2 mm. Of particular interest are the elongated bubbles

(indicative of growth near 0°C) in the rings near the growth centre of section 2 (Plate VII) which are up to 2 mm in length, and those in the surface layer (Plate VI) which are as much as 1.2 cm long. In Plate VII, a greater density of elongated bubbles in the direction of preferred growth is seen. This trend is reversed at the surface layer, where a much higher density occurs at the equator than at the pole. This can be seen most easily by comparison of sections 5 (Plate V) and 2 (Plate VI) and is also discernible in Plate III. In all the intermediate growth rings the density of bubbles is greater in the direction of preferred growth than in the equatorial direction, whilst the mean bubble diameter tends to be smaller, so that the amount of trapped gas remains roughly the same throughout the layer. There are at least three possible explanations for the mechanism of bubble trapping. In the first it is considered that the bubble rings are formed when the growing surface, with its temperature below some critical value, encounters a high density of supercooled droplets which freeze individually, and from the outside inwards. The dissolved gas which comes out of solution is then trapped within the ice. In this case the individual droplets should form many small crystals which will appear in layers (on the crossed-polaroid photographs) that coincide with the bubble layers (see Browning *et alii*³). Another possible explanation is that the growth is increased when the surface encounters a region of high liquid water content to such an extent that the rate of growth exceeds the rate at which bubbles can form and escape, and so they become trapped; however, the accreting drops are not frozen singly but are spread out over the surface forming single large crystals. This will occur at surface temperatures above some critical value, which for the 1-mm water drops impacting and freezing on single crystals studied by Hallett⁴ was -5°C . Brownscombe and Hallett⁵ found that new crystal orientations were adopted if the air temperature fell below a critical value, which was -5°C for 1-mm drops and -15°C for droplets of $20\text{-}\mu\text{m}$ radius. The third explanation suggested by Carte⁶ is that the formation of a line of bubbles depletes the dissolved gas content of the water, and so subsequent growth is necessarily bubble-free until a new and adequate supply of dissolved gas becomes available. Carte studied this mechanism in the laboratory using films of water frozen between glass plates.

In order to test Carte's findings and also to determine the manner in which lines of bubbles are deposited in a growing ice sample, a number of ice cubes were grown in a refrigerator at various temperatures. Plate IX shows a thin section of a cube grown with its base maintained at -6°C . It is easily seen that air bubbles have formed in regularly spaced lines separated by clear ice. The bubbles first appear at random points in the ice structure, and become elongated; it is interesting to note that they terminate in fairly regular lines as the ice grows into the liquid, with a region of clear ice between each bubbly layer. We note that lines of bubbles have formed during the propagation of ice through a body of water in which the rate of growth is *not* affected by the rate at which water is supplied to the growing surface—as it would be in growth by accretion—since here the total body of water frozen is made available at the outset. However, it would seem that, in both types of growth, bubble lines can be interpreted as contours marking the extent of the ice surface at any one time, and can also show the direction of growth in that the elongated bubbles terminate in regular lines on the side of the layer facing that direction. These findings support the view that the hydrometeor studied here grew in the

direction of increasing bubble-ring radii, as a hailstone would, rather than in the other direction which could be the case were it an artefact of some sort. The bubble distribution seen in the ice cube sample (Plate IX) lends support to the gas-depletion process envisaged by Carte. Whether or not the same effect may take place in an ice body growing by accretion is not clear, but it seems probable that, in order for it to occur, very thick layers of unfrozen water would have to build up on the growing surface.

In order to investigate the nature of ice growth in a container, several toy balloons were filled with water, suspended in a refrigerator and allowed to freeze. The frozen masses of water showed no tendency to produce bubbles in regular lines, but rather they were distributed in a random fashion throughout the ice sample. In addition, the direction of freezing was seen—by inspection at various times—to be from the outside inwards, leaving an unfrozen pocket of water within the frozen shell. As this pocket froze the stresses set up caused the ice shell to crack; the resultant ice structure bore no resemblance to the fragment studied here, suggesting again that the ice was not produced by freezing in a container.

The thickness of the layers in the direction of preferred growth varied from as little as 0.5 mm up to 8 mm (not counting the 20-mm thick surface layer), with 2 mm being typical. Inspection of the photographs revealed that there was a portion of a line of bubbles remaining near the growth centre. A few of these are just discernible in Plate VII. The minor axis of this line of bubbles was found to be somewhat less than 8 mm so that the original nucleus at the centre of growth was certainly no larger than this in diameter.

Examination of the photographs showed crystals ranging in size from a few millimetres to several centimetres, with the long axes of growth in the radial direction; there were no regions of small crystals coincident with the bubble rings. A few smaller crystals were apparent, distributed throughout the sample, but with a preponderance in the surface layer. The lower portion of Plate VIII shows many small crystals in the ice structure. These appeared spontaneously during melting of the specimen between glass plates to reduce its thickness from 0.5 mm to 0.2 mm. Care must be taken to identify such an event during handling of the ice samples if spurious conclusions are to be avoided.

Aircraft movement in the area. McDonald⁷ has reviewed many occurrences of falls of ice, some of which may be due to detachment from aircraft de-icing gear. In order to gain as much information as possible on the origin of the piece of ice studied here, extensive inquiries were made at Ringway, Manchester's airport for civil aircraft, which is about 8 km south of the place where the ice fell. A landing approach path from Barton Moss in the north-west takes aircraft on a course east-south-east to Stockport in the east, where the turn is made to approach the runway from the north-east. This flight path passes 1 km to the north of the junction of Burton Road with Bottesford Avenue (McLaren, Ward and Partners⁸). Two aircraft were known to have followed this approach path at around this time, one landing at 2001 GMT (a Danair Comet) and the other at 2006 GMT (a Swissair flight). No reports of icing, abnormal radio interference, antenna damage or malfunction of any kind were made to Air Traffic Control from either of these aircraft or from any others. Specific inquiries were then made of the engineers' departments handling these two flights, and it transpired that the Comet landing at 2001 GMT had

been struck on the starboard side of the nose by lightning which discharged via the elevators, although this had not been reported at the time by the captain during the approach. The flight was then referred back to Air Traffic Control, and its precise location ascertained at 1954 GMT, the time of the lightning stroke. The plane was at that moment at 8000 ft, near Barton Moss, about 20 km north-west of Manchester Airport. It subsequently dropped to 5000, 3000, 2000 and 1500 ft and made a normal 3-degree approach.

In view of the proximity of this aircraft to the area in which this lightning stroke occurred, the fact that it was struck is not altogether surprising. Since there was only one stroke, and the time and the aircraft location is known, the probable extent of the flash should be extended to at least 20 km. The way in which aircraft and thunderstorms interact has been studied by several people, notably Byers and Braham,⁹ Newman¹⁰ and Vonnegut.¹¹ From considerations of the probability of an aircraft being struck by lightning, Vonnegut, drawing on Newman's data, tentatively suggests that the presence of an aircraft may increase the probability of a lightning stroke occurring. The circumstances of the lightning described here support this suggestion, since the aircraft may very well have been responsible for initiating the flash in a region of electrified cloud where the field intensity was insufficient to generate the discharge by more conventional means, which are assumed to require higher fields because of the small size of particles (of rain, snow or hail) involved. The absence of any subsequent lightning further indicates that the electrical development of the storm was insufficient to give rise to naturally initiated discharges.

Weather conditions in the area. The nearest upper-air sounding station to Manchester is about 40 km distant at Aughton, near Liverpool. The following ascent was recorded at 0000 GMT on Tuesday, 3 April: wind direction and speed at the surface and at 1.5 and 3.0 km altitude, 350° 7 kt, 330° 34 kt and 330° 41 kt respectively; air temperature 2.5°C at the surface, 0°C at 2.5 km and -31°C at 4.5 km; cloudbase 600 m. These wind-shear figures are comparable with those recorded at the time of the storm of 1 July 1968 near Cardiff in which giant hailstones fell, as described by Macklin *et alii*.¹² The 24-hour reports for 2 April 1973 show the following rainfall values in the vicinity: Southport 20 mm, Blackpool 25 mm, Morecambe 25 mm, Douglas 28 mm, Manchester Airport 18 mm; hail was recorded at Douglas and Anglesey. The Manchester 10-year averages for the months of March and April are 53 mm and 66 mm respectively and the annual rainfall is 888 mm. It is noted that the 24-hour rainfall figure constitutes one-third to one-half of the monthly average.

Comments on the origin of the ice hydrometeor. To make a definitive statement on this question is a very difficult task. The properties of the ice sample are in some ways very much like those of a hailstone. However, the size of the fragment suggests that the original may have weighed as much as 1.0 to 2.0 kg, which is large even compared to the Coffeyville hailstone which weighed 0.76 kg (Knight and Knight¹³). On the other hand, the nucleus of growth was less than 10 mm in diameter. If such a large growth of ice built up on an aircraft, it would need to be on something like a radio antenna or some other component of small size. The aerodynamic forces on such a body

would be enormous at normal flight speeds, even when making the slow landing approach, and it seems unlikely that there would be no damage to the component. Further, specific inquiries showed that no damage had been reported by the aircraft on the flight path in question, or indeed by any others in the air at the same time, other than the lightning strike to the Danair Comet at 1954 GMT, which landed before the ice fell. Again, the shape of an ice growth starting from a small nucleus on an aircraft at normal flight speed would be expected to exhibit far greater elongation in the airstream direction than is displayed by this body, where the degree of growth in the directions parallel and perpendicular to the major axis is the same within a factor of 2; such a mode of growth is consistent with all known characteristics of hailstones and it is hard to visualize how it could have occurred on an aircraft. Furthermore, if such a heavy growth accumulated at one location on an aircraft, one would expect heavy icing over the rest of the forward-facing surfaces, and, as stated previously, such icing was not reported on any aircraft in the air at the time.

The ice sample displays a puzzling collection of features. Whilst it is clearly composed of cloud water, there is no conclusive evidence enabling one to decide precisely how it grew, except that laboratory tests suggest that this sample did not grow in a container. In some respects it is very much like a hailstone, whilst in others it is not. Equally, the possibility that it was formed by icing on an aircraft is not borne out by the flight records. The author welcomes correspondence on this open question.

Acknowledgements. The author wishes to express his gratitude to the following, whose co-operation in various ways expedited the preparation of this report: the Airport Director, the Clerk to the Airport Committee of Manchester Corporation, and the Air Traffic Control Department of the Civil Aviation Authority for information about flight paths into and out of Manchester Airport and aircraft movements on 2 April 1973; the engineer's departments of Swissair and Danair for the specific reports on the two aircraft; Manchester Weather Centre for meteorological records; Mr M. Hambrey of the Geography Department of Manchester University for his helpful discussion and for permission to use the universal stage on which the crossed polaroid photographs were taken; his colleague, Mr M. J. Gay of this department, for the use of his camera, with which all the photographs were taken; and finally to Dr S. C. Mossop for his discussion and helpful suggestions.

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551-554

VERTICAL WIND SHEAR IN THE LOWEST 600 METRES AT SHOEBOURNNESS

By M. J. DUTTON

Summary. An analysis of vertical wind shear in the lowest 600 metres at Shoeburyness using 5 years of day-time pilot-balloon soundings has shown that the largest day-time shears in the layer between the surface and a height of 50 metres occur most frequently in conditions of general free convection with moderate to strong surface winds off the land, and are probably mainly attributable to the natural gustiness of the wind in these lowest layers. Overall, 21 per cent of shears exceeded $80 \text{ m s}^{-1} \text{ km}^{-1}$ ($4.74 \text{ kt per } 100 \text{ ft}$) and 1.7 per cent of shears exceeded $160 \text{ m s}^{-1} \text{ km}^{-1}$ ($9.47 \text{ kt per } 100 \text{ ft}$); 1.2 per cent exceeded $10 \text{ kt per } 100 \text{ ft}$.

A limited comparison of Shoeburyness with Larkhill (an inland site) for the surface-200-m layer showed no significant difference between the derived shear-frequency distribution for the two sites.

Introduction. Vertical wind shear is obviously an important factor in the safety of landing and take-off operations, and it is generally recognized that the final 60 metres or so of descent of a landing aircraft are the most critical. In particular, for a large aircraft on approach to touchdown, the effects of a rapidly decreasing head-wind component (that is to say rapid loss of airspeed) during the last 60 metres of descent could prove disastrous.

The International Civil Aviation Organization (ICAO)¹ has made several recommendations concerning wind-shear conditions during landing and take-off phases. Among these recommendations was an interim shear criterion (5th Air Navigation Conference of ICAO, 1967), namely that vertical wind shear, when reported quantitatively, should be expressed according to the following classification:

Category	Magnitude of shear		
	<i>m/s per 30 m</i>	<i>m/s per km</i>	<i>kt per 100 ft</i>
Light	0-2.5	0-83	0-4.9
Moderate	2.5-4.5	83-150	4.9-8.9
Strong	4.5-6.0	150-200	8.9-11.7
Severe	>6.0	>200	>11.7

This classification was not officially accepted because it cannot apply universally to all types of aircraft.

In 1973 a question about the frequency of occurrence of strong vertical wind shear in the lowest layers at a coastal site arose out of the requirement for a third London Airport at Maplin: how did the frequency of occurrence compare with that at a typical inland site? This report presents the results of an analysis of five years (1968–72) of day-time pilot-balloon ascents at Shoeburyness to produce a climatology of vertical wind shear across various layers (ranging in thickness from 40 m to 400 m) from the surface up to 600 m. It should be stressed from the outset, however, that ‘vertical wind shear’ in the context of this paper does not refer to the true vertical shear of the mean wind but to an *apparent* vertical wind shear, the difference between a balloon-sensed wind averaged over a layer and a surface wind averaged at a fixed point (or another balloon-sensed wind) divided by the thickness of the layer across which the wind change is measured. This point should be borne in mind in the interpretation of the results.

The report incorporates the results of a similar analysis of five years’ (1968–72) pilot-balloon ascents at Larkhill, an inland site, for comparison with the Shoeburyness results. Direct comparison of the results is limited to the surface–200-m layer since the rates of balloon ascent used at Larkhill were normally too large to allow finer resolutions in the vertical. The comparison is also limited to morning ascents, as the Larkhill soundings took place at or near 0900 (all times in this paper are expressed in Greenwich Mean Time and are nominal times, the actual ascents having taken place within ± 30 minutes of the exact hour).

The observations

Shoeburyness. All the pilot-balloon soundings (for which the requisite information was available) at Shoeburyness from 1968 to 1972 inclusive (5 years) provide the basic observations. The balloon was tracked by single theodolite until a sufficiently accurate radar fix was obtained, normally at two minutes from balloon-release time; the radar slant range was not accurately measurable when less than 500 metres. In consequence the great majority of ascents include theodolite fixes (elevation and azimuth) at $\frac{1}{2}$ minute and 1 minute with a radar fix (elevation, azimuth, and height derived from elevation and range) at 2 minutes. The balloon heights at $\frac{1}{2}$ minute and 1 minute were usually subjectively interpolated, the radar-allocated heights being used at and after 2 minutes.

Only the first two minutes of each sounding were required for this investigation, so that the $\frac{1}{2}$ -minute, 1-minute and 2-minute balloon fixes (elevation, azimuth, height) together with a surface (10-m) wind, measured close to the balloon-release site, provided all the necessary data. The surface wind is an average of 10 spot readings, 5 taken over a period of 1 minute immediately before balloon release, and a further 5 over a period of 1 minute immediately following termination of the ascent (typically 10 to 15 minutes after balloon-release time).

At Shoeburyness all the ascents are restricted to day-time. Soundings are made at various times but normally at 0800/0900 on weekdays (Monday to Friday); in addition a sounding is usually made at 1200/1300. If no firing exercises have been planned no ascent is made at 1200/1300. The exercises are usually planned a few days in advance. Occasionally, in adverse weather conditions such as bad visibility, strong winds or the presence of a marked

temperature inversion, the exercise may be cancelled and no sounding be required, but this happens very infrequently; any resulting bias in the sample of soundings made at 1200/1300 is only very slight. The soundings made at 0800/0900 can be considered meteorologically as being relatively unbiased.

Table I shows the distribution of ascent times; 48.7 per cent of all ascents took place at 0800 or 0900 and 37.6 per cent took place at 1200 or 1300.

TABLE I—TIME DISTRIBUTION OF ASCENTS (SHOEBURYNNESS)

Time (GMT) \pm 30 min	5	6	7	8	9	10	11	12	13	14	15	16	17	18
No. of ascents	5	23	37	729	158	58	73	550	136	23	20	7	3	1
Total number of ascents = 1823.														

The balloon rates of ascent used at Shoeburyness varied widely but the great majority were in the broad range of 100 to 300 metres per minute.

Larkhill. Again, pilot-balloon soundings at Larkhill from 1968 to 1972 provide the basic observations, but there were some major differences in the details of the standard ascent procedure. The ascents at Larkhill did not include a $\frac{1}{2}$ -minute balloon fix; in addition all the soundings took place between 0700 and 1000 with 94 per cent of them at 0900 (Table II) and the ascent rates used were generally greater than those at Shoeburyness.

TABLE II—TIME DISTRIBUTION OF ASCENTS (LARKHILL)

Time (GMT) \pm 30 min	..	7	8	9	10
No. of ascents .. .. .	..	9	5	714	31
Total number of ascents = 759.					

Analysis of observations. The derived layer-meant winds were imputed to the layer mid-points in the normal way; for each Shoeburyness ascent four winds were available whereas each Larkhill sounding yielded three winds. The vector wind shear, \mathbf{S} , across a layer was defined as the magnitude of the vector wind change across the layer divided by the layer thickness:

$$\mathbf{S} = \frac{\mathbf{u}(h_2) - \mathbf{u}(h_1)}{h_2 - h_1},$$

where $\mathbf{u}(h_1)$ and $\mathbf{u}(h_2)$ are the winds at heights h_1 and h_2 ($h_2 > h_1$) and $S = \pm |\mathbf{S}|$.

S was defined as positive if $|\mathbf{u}(h_2)| \geq |\mathbf{u}(h_1)|$ (wind speed increasing or constant with increasing height) and negative otherwise. With this system (PIBAL) of determining the vertical wind shear, the derived shear, S , is not a measure of the true vertical shear of the mean wind but an *apparent* vertical wind shear, the difference between

- (a) a balloon-sensed wind averaged over a layer, and
- (b) either a surface wind averaged at a fixed point or another balloon-sensed wind;

divided by the thickness of the layer across which the wind change is measured. This is an important point and its implications will be discussed later.

To simplify the analysis a degree of layer standardization was introduced. At Shoeburyness each actual layer was assigned one of the nominal layers 10–50 m, 10–100 m, 10–200 m, 10–400 m, 50–100 m, 50–200 m, 50–400 m, 100–200 m, 100–400 m and 200–400 m. For Larkhill ascents only three nominal layers were used, namely 10–200 m, 10–600 m and 200–600 m.

The Shoeburyness analysis included categorization in terms of time of ascent (0500–1000) and (1100–1800), season (the four main seasons) and surface wind direction ('sea' winds 040–219 degrees and 'land' winds 220–039 degrees). The Larkhill shears were categorized by season only.

Mean wind profiles for the Shoeburyness ascents were also computed; these were categorized by time of ascent (as above), season (summer half-year and winter half-year) and surface wind direction (300–039° open country with few towns; 040–149° open sea—long fetch; 150–239° sea/estuary—shorter fetch; 240–299° including built-up areas). For each category mean profiles of \bar{u}/\bar{u}_{10} , the ratio of mean wind speed to 10-m mean wind speed, and wind-direction veer, defined as zero at the surface, were computed. To eliminate some of the very large wind-direction variations with height which often occur in calm or light-wind conditions, the wind profiles were constructed using only ascents for which the surface wind speed exceeded 4 kt.

Errors of measurement. The error in the shear derived from single-theodolite/pilot-balloon measurements is dependent on the errors in elevation, azimuth, allocated height (these determine the error in the mean wind imputed to the layer mid-point) and, for shears across layers with base at the surface, the surface wind. Estimates can be made of the likely root-mean-square (r.m.s.) errors in the measured variables involved in the computation of shear magnitude, the two most important errors, particularly for shears in the lowest 50 metres, being elevation (especially at low elevation) and allocated balloon height. As has already been pointed out, the $\frac{1}{2}$ -min heights are allocated, not by assuming a constant rate of ascent, but by subjective interpolation using radar fixes at and after 2 minutes, so the level of r.m.s. error in allocated balloon height is obviously reduced appreciably from that applicable to ascents in which tracking by single theodolite alone is used and a constant rate of ascent is assumed for the balloon. The 2-min radar fix is sufficiently accurate to provide a good measure of the mean ascent rate through the lowest 400 m or so (the 2-min height in fact varied widely in the range 250–600 m); the mean effect (smoothed over the lowest 400 m) of vertical air motions is therefore effectively implicit in the derived $\frac{1}{2}$ -min and 1-min balloon heights. What we cannot know about, however, is the sub-structure of the vertical motion within this surface–400-m layer, and we can expect errors in allocated heights at $\frac{1}{2}$ minute and 1 minute (particularly the former) to be largest when the variations with height (within this layer) of the ascent rates are large. Typical conditions in which the variations might be appreciable are those in which a relatively shallow convection layer near the surface is capped by a stable layer.

It so happens in fact that, in the lowest layer, the computed shear, which is the difference between the measured winds at two levels divided by the thickness of the intervening layer, is not as sensitive to the size of the ascent-rate error as might at first appear to be the case, since the errors in both the numerator and denominator of the division are always in the same sense, that is to say an overestimate of the balloon height (and therefore of the layer thickness) produces an overestimate of the wind difference, and vice versa.

Typically, in conditions of moderate to strong shear, the r.m.s. error in the computed shear magnitude across the lowest layer at a balloon elevation of 10° and $\frac{1}{2}$ -minute allocated balloon height of 100 m is about 30 to 40 m s⁻¹ km⁻¹

(1.8 to 2.4 kt per 100 ft). An overall value applicable to all moderate/strong wind occasions would be about 25 to 30 m s⁻¹ km⁻¹.

Discussion of results

Shoeburyness

(a) *Lowest layer—surface to 50 m.* The level of error in the computed shear magnitudes is quite high for this layer and the derived shear-frequency distributions must be treated with due caution, particularly in any detailed examination of the frequencies of the largest shears. Despite this, some interesting conclusions about the variation with different categories (time, season, surface wind direction) of the shear-frequency distributions can be drawn.

- (1) *Frequencies of shear magnitudes ≥ 80 m s⁻¹ km⁻¹* (Table III). The figures show that significantly more of these shears occur with 'land' winds (220–039°) than with 'sea' winds except in winter; in the winter/1100–1800 category the difference is strikingly reversed.

For each of the wind direction/time categories except 'land'/1100–1800 the maximum frequencies are in winter. For the 'land'/1100–1800 category the minimum frequency is in winter, with maximum in spring and summer, both the spring and summer frequencies of these moderate to severe shears being approximately double the winter frequency.

The frequencies for 'sea' winds, for each of the seasons, show no significant variation with time category, although the all-year figures show a marginally greater frequency for the 0500–1000 period. For 'land' winds, however, the larger frequencies in the 1100–1800 period in spring and summer are significant, as is the decreased frequency in the same time category in winter.

- (2) *Frequencies of shear magnitudes ≥ 160 m s⁻¹ km⁻¹* (Table IV). The limited number (total of 29 in 5 years) of these large shears makes it difficult to assess the significance of any of the observed variations in frequencies of occurrence from category to category but it is encouraging that most of the variations are broadly similar to those found for the shears discussed above.

The figures in Table IV show that these large shears occurred more frequently in 'land' winds except in the winter/0500–1000 category; in fact 23 out of 29 of these shears occurred in 'land' winds. For 'sea' winds, in the 0500–1000 period the frequencies are about 1 per cent for each of the seasons, and again, as for the moderate to severe shears, the 1100–1800 frequencies are greater (for all seasons) than the 0500–1000 frequencies, with the minimum 1100–1800 frequencies in winter. Over the year as a whole, shear magnitudes exceeded 160 m s⁻¹ km⁻¹ on 1.7 per cent of occasions, 10 kt per 100 ft on 1.2 per cent of occasions, and 6 m/s per 30 m or 200 m/s per km on 0.5 per cent of occasions.

Closer study of the 17 largest measured shears ($S \geq 180$ m s⁻¹ km⁻¹) showed that most occurred at 1200 and all but one occurred when the surface wind direction was in the range 220 to 320 degrees. The lowest surface wind speed associated with these largest shears is 6 m/s, and one possibility which springs to mind initially is that the large shears may simply be associated with occasions when the r.m.s. errors were likely to be large. (Strong winds, implying low initial elevation angles, produce the largest errors). But simple chi-square tests on the relationship between the incidence of large shears and moderate to

TABLE III—SHOEBURYNNESS, SURFACE TO 50 METRES, PERCENTAGE FREQUENCIES OF WIND SHEAR EQUAL TO OR EXCEEDING $80 \text{ m s}^{-1} \text{ km}^{-1}$ ($4.74 \text{ kt PER } 100 \text{ ft}$)

Surface wind direction	Time	Winter	Spring	Summer	Autumn	Year
040–219° (‘sea’)	0500–1000	33.8	9.5	5.1	12.8	16.4
	1100–1800	29.1	10.1	8.2	8.2	13.5
220–039° (‘land’)	0500–1000	35.0	22.6	18.6	21.2	23.7
	1100–1800	17.8	33.8	34.6	27.8	28.1
All	0500–1000	34.5	18.2	13.8	18.4	21.0
	1100–1800	22.8	23.4	19.6	19.5	21.1
All	All (0500–1800)	28.9	20.1	16.4	18.7	21.0

TABLE IV—SHOEBURYNNESS, SURFACE TO 50 METRES, PERCENTAGE FREQUENCIES OF WIND SHEAR EQUAL TO OR EXCEEDING $160 \text{ m s}^{-1} \text{ km}^{-1}$ ($9.47 \text{ kt PER } 100 \text{ ft}$)

Surface wind direction	Time	Winter	Spring	Summer	Autumn	Year
040–219° (‘sea’)	0500–1000	5.0(5)	0.0	0.0	0.0	1.5(5)
	1100–1800	0.0	0.0	0.9(1)	0.0	0.3(1)
220–039° (‘land’)	0500–1000	0.8(1)	0.6(1)	1.4(2)	1.2(2)	1.0(6)
	1100–1800	2.0(2)	5.0(5)	3.7(3)	7.0(7)	4.5(17)
All	0500–1000	2.8(6)	0.4(1)	0.8(2)	0.8(2)	1.1(11)
	1100–1800	1.2(2)	2.9(5)	2.2(4)	4.1(7)	2.4(18)
All	All (0500–1800)	1.9(8)	1.3(6)	1.4(6)	2.0(9)	1.7(29)

Figures in brackets represent numbers of cases.

strong surface winds ($u_{10} \geq 5 \text{ m/s}$) from various directions indicate that the relative incidence of large shears for winds in the 120-degree direction range $210\text{--}329^\circ$ is significantly higher than for winds in the ranges $330\text{--}089^\circ$ and $090\text{--}209^\circ$. This is so, both for the 17 shears with $S \geq 180 \text{ m s}^{-1} \text{ km}^{-1}$ and for the 29 shears with $S \geq 160 \text{ m s}^{-1} \text{ km}^{-1}$, and it does not support the view that the largest measured shears occur because of large errors due to strong winds.

A study of the synoptic situations associated with the incidence of large shears revealed that, of the 17 largest shears, 13 occurred in generally free-convective conditions with moderate to strong surface winds (implying near-neutral stability in the lowest layers), and usually with showers reported in the vicinity. One way in which this bias of large measured shears towards moderate/strong wind conditions may be explained involves the natural gustiness of the wind near the surface. It has already been pointed out that the measured surface–50-m shear is effectively the difference between the balloon-sensed wind (averaged over the layer from the surface to about 100 m and over 30 seconds following the motion of the air) and the surface wind measured near the balloon release point. From the results of various studies of the relationship between Lagrangian (‘following the motion’) and Eulerian (‘fixed-point’) wind statistics, summarized for example by Pasquill,² we can estimate that, typically, with moderate/strong winds and near-neutrally stable conditions in the lowest 100 m, a balloon-sensed (Lagrangian) 30-second wind is equivalent to something like a 5-second fixed-point (Eulerian) wind. In other words, the wind with which the balloon is carried along in the first 30 seconds of flight is approximately equivalent to the layer wind averaged (at the release point) over the 5 seconds immediately following the balloon release time. By assuming

that in moderate/strong winds there is no significant bias towards releasing the balloon in lulls (or gusts) it is therefore possible to carry out a simple analysis to determine the expected distribution of large measured shears produced by the natural variability of the 5-second fixed-point winds (assuming also that the measured shears are normally distributed about the mean shear). Then, from estimates, for near-neutral steady-state boundary-layer conditions in moderate/strong winds, of the mean surface–50-m shear and its variance, made up of the contributions from the natural variability of the 5-second winds and that from the errors of measurement, we can estimate an expected probability of occurrence of any magnitude of measured shear for a given surface wind speed. So, given a large number of ascents we can compute an expected distribution of large measured shears from a knowledge of the surface wind speed and direction frequencies.

The mean shear can be obtained from the logarithmic law for neutral stability:

$$\frac{\bar{u}_h}{\bar{u}_{10}} = \frac{\log(h/z_0)}{\log(10/z_0)}, \text{ (for } h \gg z_0),$$

using appropriate roughness lengths* (z_0) for different wind directions; estimates of the variance contribution from the variability of the 5-second winds can be inferred from the work of Durst³ and many others. Estimates of the r.m.s. measurement errors have already been discussed. In applying the logarithmic law to the Shoeburyness wind-speed profiles, roughness lengths ranging from 0.5 cm for 'sea' winds to 20 cm for westerly 'land' winds have been used. The different roughness lengths used for different directions obviously also imply different 5-second wind variances since larger roughness lengths imply greater wind variability near the surface.

For each wind speed/direction category a computed mean shear and associated expected standard deviation imply an expected normal distribution of measured shear. By summing the individual distributions from all the wind speed/direction categories, an overall expected shear distribution for the large shears ($\geq 100 \text{ m s}^{-1} \text{ km}^{-1}$ say) can be obtained.

The results of this analysis are shown in Table V. For 'sea' winds the observed frequency of shears $\geq 120 \text{ m s}^{-1} \text{ km}^{-1}$ is almost four times as great as that predicted. For 'land' winds the distributions are in much better agreement although the difference between them is significant almost solely because of the large difference between the numbers of the largest shears ($S \geq 180 \text{ m s}^{-1} \text{ km}^{-1}$).

TABLE V—SHOEBURYNESS, SURFACE TO 50 METRES, COMPARISON OF PREDICTED AND OBSERVED WIND SHEAR FREQUENCY DISTRIBUTIONS

	Shear ($\text{m s}^{-1} \text{ km}^{-1}$)								Totals
	<60	60–80	80–100	100–120	120–140	140–160	160–180	≥ 180	
Expected (sea)	555	75	35.7	13.6	4.2	1.2	0.3	—	685
Observed (sea)	485	98	49	32	11	4	5	1	685
Expected (land)	613	144	100	61	33.3	17.9	8	6.7	984
Observed (land)	580	154	107	61	43	16	7	16	984

* The roughness length is effectively a measure of the roughness of the underlying surface.

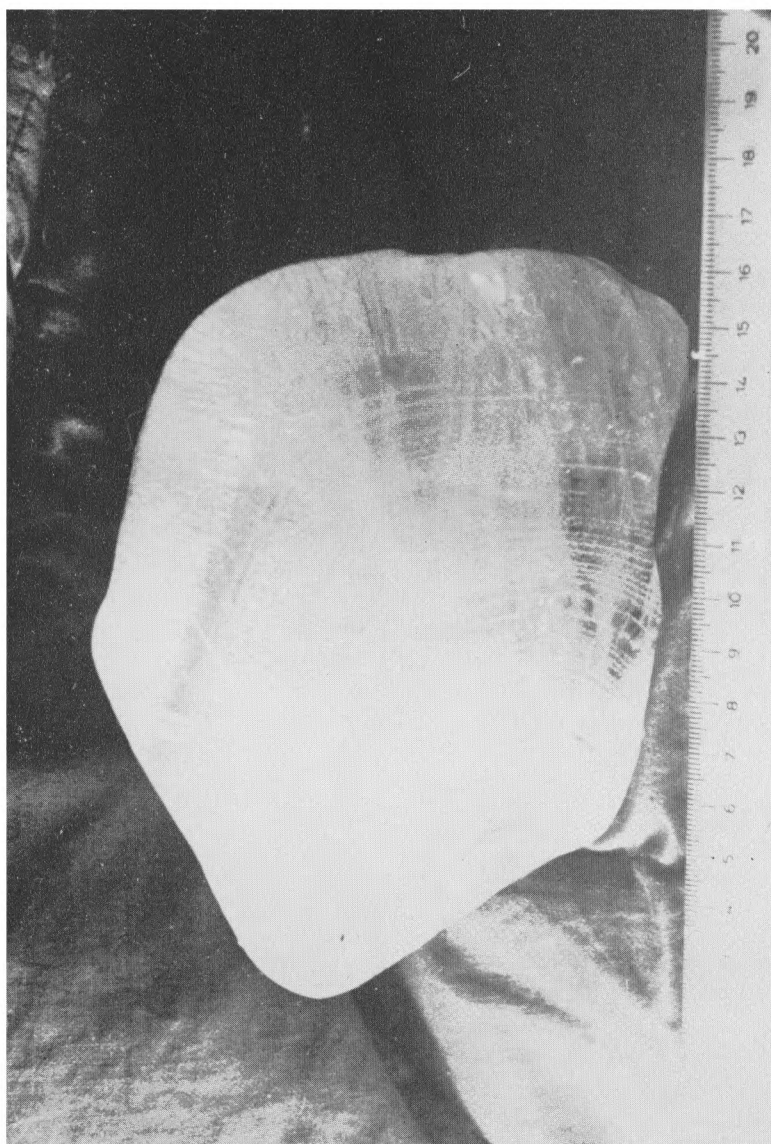


PLATE I—A VIEW OF THE FRAGMENT BEFORE SECTIONING, SHOWING THE LAYERED
STRUCTURE
The scale is in centimetres.

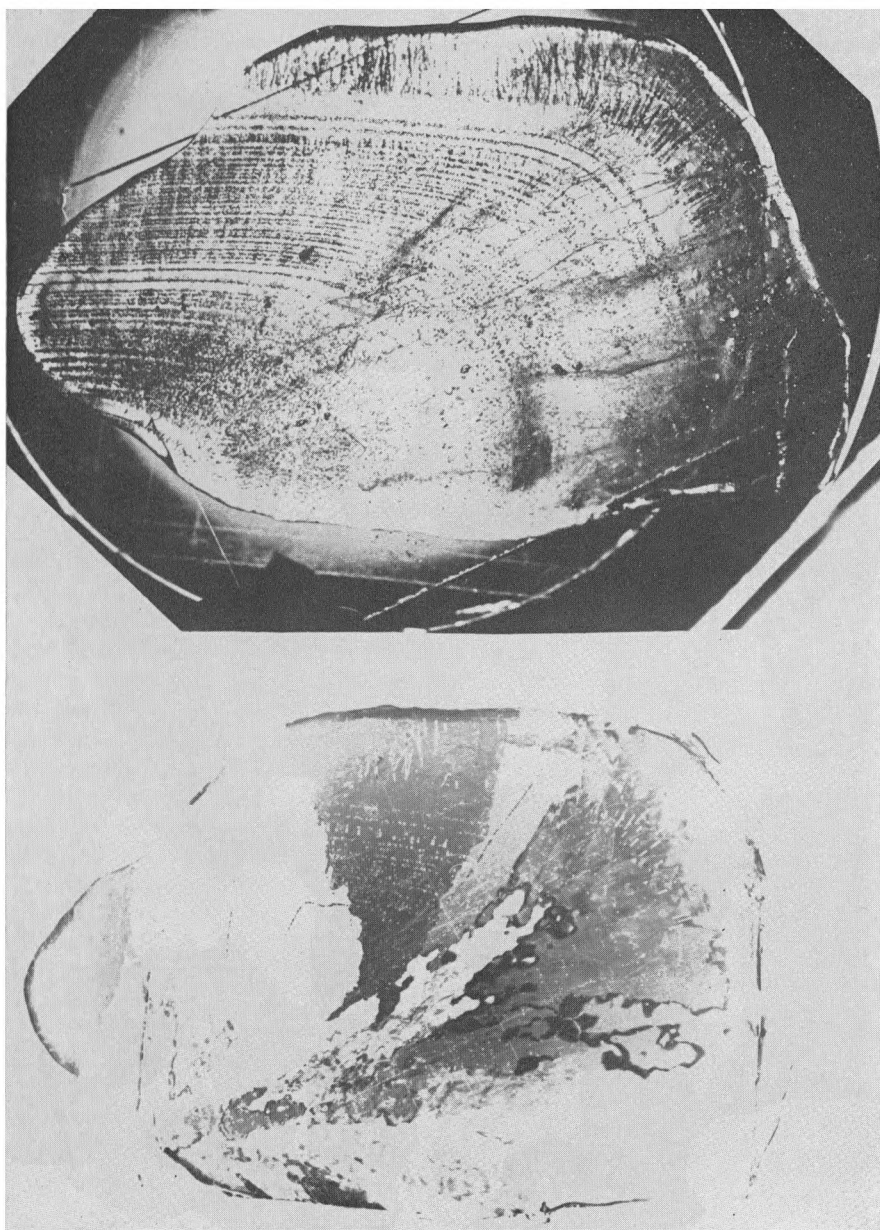


PLATE II—A PHOTOGRAPH OF SECTION I

The upper view shows the layer and bubble structure in transmitted light; the lower view shows the crystal fabric between crossed polaroids. The longest dimension of the sample is 13 cm.

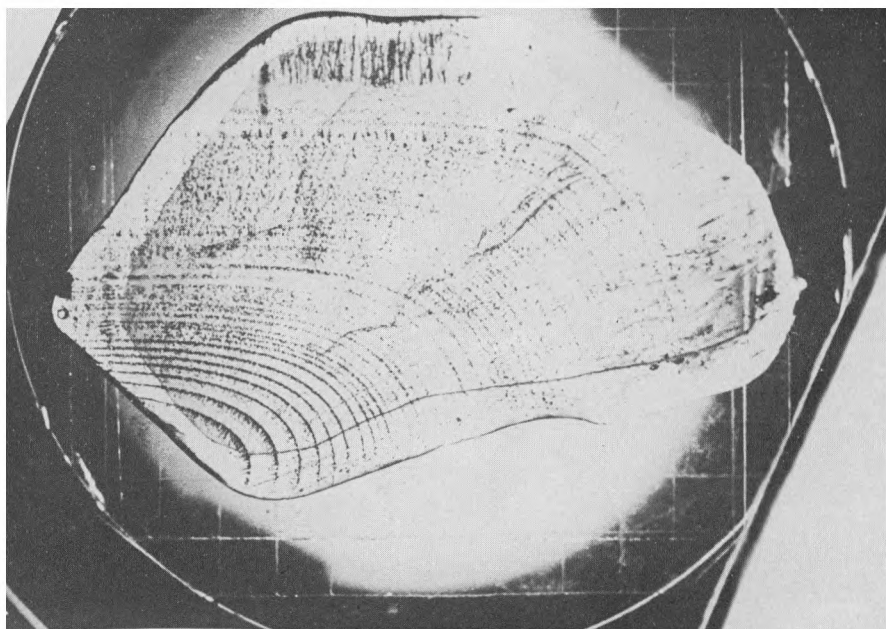


PLATE III—A PHOTOGRAPH OF SECTION 2
Comments are as for Plate II. Longest dimension is 12 cm.

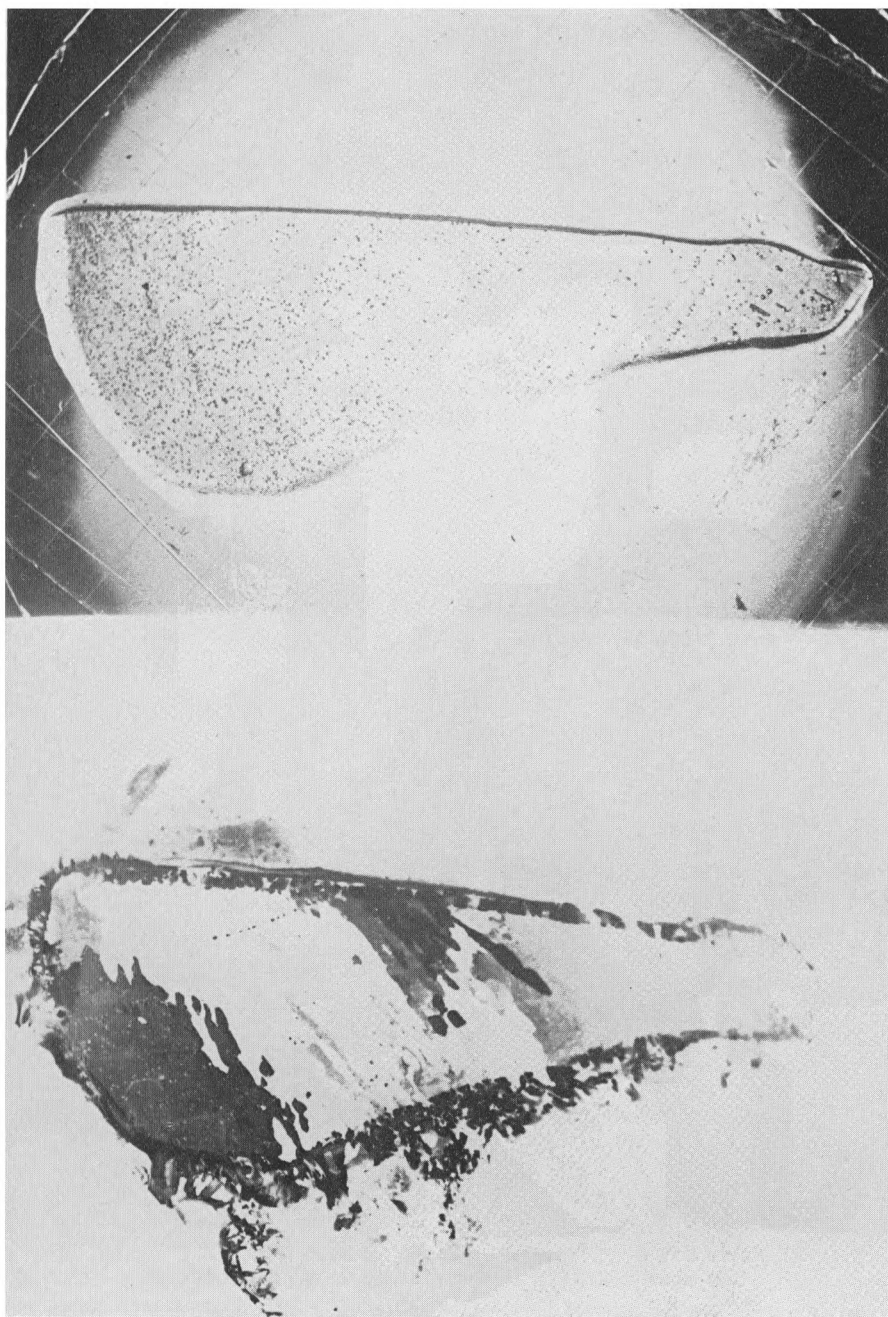


PLATE IV—A PHOTOGRAPH OF SECTION 3
Comments are as for Plate II. Longest dimension is 11.5 cm.

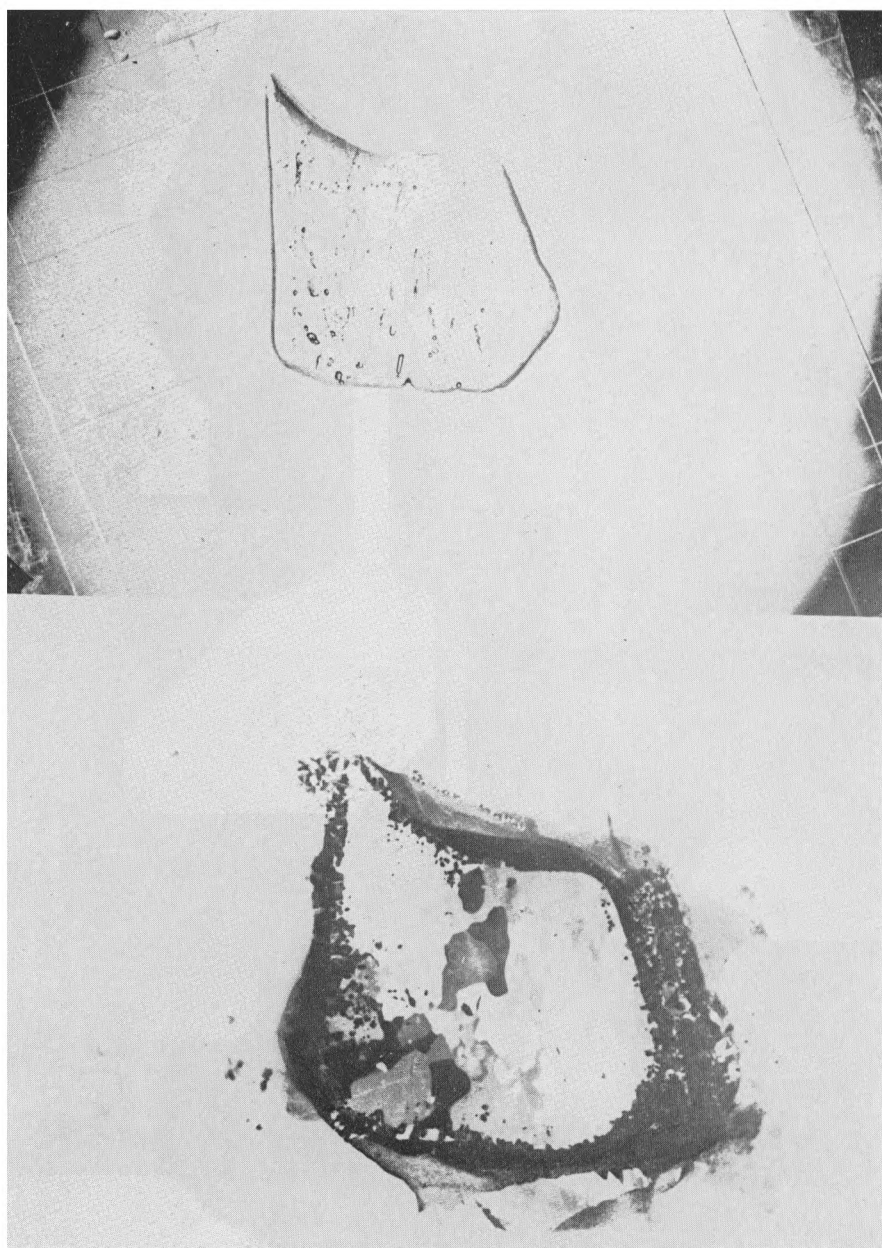


PLATE V—A PHOTOGRAPH OF SECTION 5
Comments are as for Plate II. Longest dimension is 5 cm.

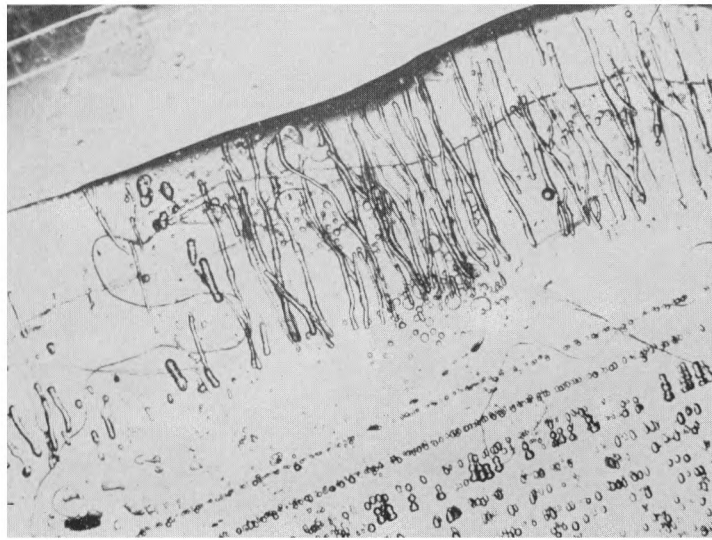


PLATE VI—SECTION 2: CLOSE-UP OF THE EQUATORIAL
SURFACE LAYER

Distance from the line of small non-migrating bubbles to the surface
is about 2 cm and the surface layer of migrating bubbles is 1.2 cm
thick.

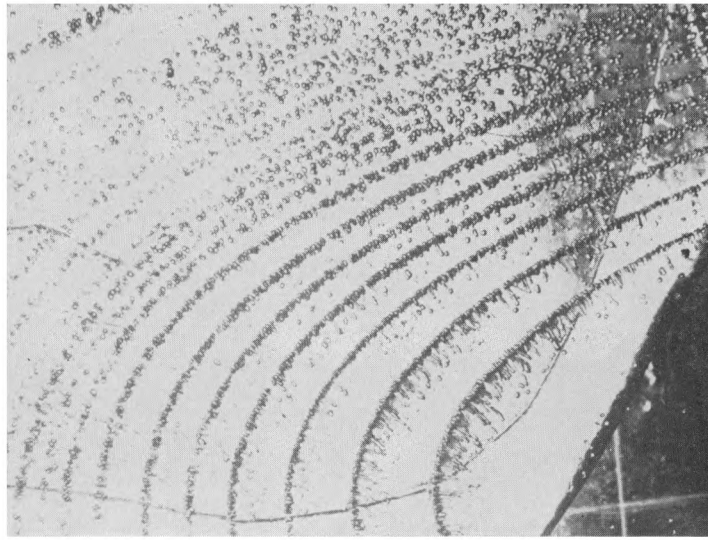


PLATE VII—SECTION 2: CLOSE-UP OF THE GROWTH RINGS
NEAR THE CENTRE

The long axis of the photograph represents 5 cm.



PLATE VIII—SECTIONS 3 (UPPER) and 6 (LOWER) AT TWO STAGES OF RECRYSTALLIZATION INDUCED IN A THIN LAYER BY MELTING BETWEEN TWO GLASS PLATES
Section 6 is 0.2 mm thick at this stage and its longest dimension is 2.7 cm.

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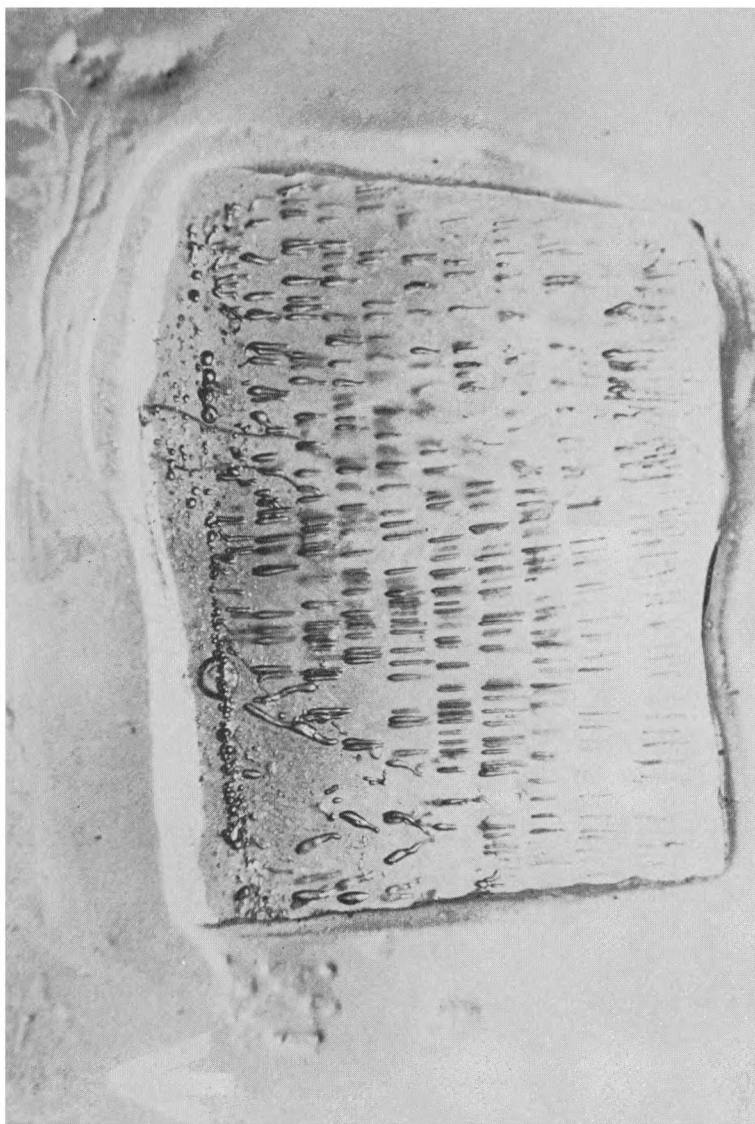


PLATE IX—A THIN SECTION OF AN ICE CUBE GROWN WITH ITS BASE MAINTAINED AT -6°C

The lines of trapped bubbles are clearly seen, the elongation being in the direction of growth, as indicated by the arrow.

The main shortcomings of the application of this method of predicting the distribution of large measured shears in moderate/strong winds are:

- (1) Non steady-state cases, where there may be large changes of wind direction and/or speed during the period of the ascent, are not allowed for. Exclusion of such cases reduces the predicted occurrence of large shears.
- (2) The necessary assumption that there is no significant bias towards releasing the balloon in lulls is only strictly valid in the strongest wind conditions. This assumption obviously therefore produces overestimates of the occurrence rates of the larger shears.

However, the analysis does appear to predict quite well the frequency distribution of shears in excess of $60 \text{ m s}^{-1} \text{ km}^{-1}$ with winds off the land and probably explains why the majority of the largest shears occur in 'land' winds. For 'sea' winds the analysis significantly underestimates the frequency of shears in excess of $100 \text{ m s}^{-1} \text{ km}^{-1}$; this discrepancy may be due to a combination of two main factors:

- (1) The roughness length applicable to moderate/strong 'sea' winds can vary considerably depending on the exact nature of the sea surface; it may often exceed the assumed overall value of 0.5 cm , particularly in strong winds with a very disturbed sea surface. Use of the higher values of roughness length for strong winds would increase the expected number of the largest shears.
- (2) Modification of the mean profile and turbulence intensity may sometimes be significant during passage of the air over the short distance from the coastline to the sampling point, particularly when the land is much warmer than the sea.

(b) *Surface to 100 m.* Across this layer there were no measured shear magnitudes in excess of $160 \text{ m s}^{-1} \text{ km}^{-1}$; the largest shear was $137 \text{ m s}^{-1} \text{ km}^{-1}$ ($8.1 \text{ kt per } 100 \text{ ft}$). Table VI contains the percentage frequencies of $S \geq 60 \text{ m s}^{-1} \text{ km}^{-1}$ ($3.55 \text{ kt per } 100 \text{ ft}$); this threshold was chosen in preference to the $80 \text{ m s}^{-1} \text{ km}^{-1}$ used for the surface–50-m shears because there were so few shears exceeding that magnitude in this layer (19 in all, representing 2.6 per cent of all shears in this layer).

The seasonal variations are quite well defined for these shears, with the maxima usually in winter and minima in summer.

TABLE VI—SHOEBURYNNESS, SURFACE TO 100 METRES, PERCENTAGE FREQUENCIES OF WIND SHEAR EQUAL TO OR EXCEEDING $60 \text{ m s}^{-1} \text{ km}^{-1}$ ($3.55 \text{ kt per } 100 \text{ ft}$)

Surface wind direction	Time	Winter	Spring	Summer	Autumn	Year
040–219° (‘sea’)	0500–1000	19.5(9)	12.9(5)	5.0(1)	9.5(4)	12.9(19)
	1100–1800	6.5(3)	4.2(2)	2.0(1)	0.0	3.4(6)
220–039° (‘land’)	0500–1000	12.7(6)	6.4(4)	4.5(3)	10.9(6)	8.2(19)
	1100–1800	11.3(5)	8.2(4)	8.0(4)	8.5(4)	8.9(17)
All	0500–1000	16.1(15)	9.0(9)	4.7(4)	10.3(10)	10.1(38)
	1100–1800	18.9(8)	6.2(6)	5.0(5)	4.9(4)	6.3(23)
All	All (0500–1800)	12.6(23)	7.0(15)	4.8(9)	7.9(14)	8.2(61)

Figures in brackets represent actual numbers of cases.

(c) *All other nominal layers.* Table VII and Table VIII (a)–(c) summarize the main results for all nominal layers including those already discussed in detail above. Table VII lists the largest measured shears for each of the nominal layers; Table VIII lists the percentage frequencies of $S < 0$ (negative shears), $0 \leq S < 80$ and $S \geq 80 \text{ m s}^{-1} \text{ km}^{-1}$ for three of the most relevant categories. In the higher nominal layers, particularly in the 100–200-m layer, the relatively high frequencies of negative shears are interesting. In the 100–200-m layer 36.9 per cent of all shears were negative; for summer this figure rises to 50 per cent for all directions, and 65 per cent when only ‘land’ winds were considered.

(d) *Mean wind profiles.* The computed mean wind profiles (wind speed as a proportion of surface wind speed, and veer from surface wind direction) are shown in Figures 1(a)–(d); they include only those ascents in which the surface wind exceeded 4 kt, for the reasons given in the ‘Analysis of observations’ section. Note that the season and wind-direction categories differ from those used in the analysis of vertical wind shear. (In the figures, N is the total number of cases sampled in the lowest levels, up to at least 200 m, and N' is the number sampled at the level where the profile terminates.)

Larkhill/Shoeburyness comparison—surface to 200 m. For reasons already explained, direct comparison between Shoeburyness and Larkhill vertical wind-shear frequency distributions is unfortunately limited to only one nominal layer, the surface–200 m layer, and to one time category, 0500–1000 (0700–1000 for Larkhill).

Table IX compares the distributions for this layer at Shoeburyness (0500–1000) and Larkhill (0700–1000), taking into account all surface wind directions at both sites. Although the figures show that there were consistently slightly more of the largest shears ($S \geq 40 \text{ m s}^{-1} \text{ km}^{-1}$) at Shoeburyness, none of the differences are statistically significant. In comparing the figures it should be borne in mind that the bulk of the Shoeburyness 0500–1000 soundings used in the analysis took place at 0800 (72 per cent), with some at 0500–0700 (6.5 per cent), whereas 94 per cent of the Larkhill 0700–1000 soundings took place at 0900, with only 1.8 per cent before this time at 0700–0800. On the simple basis therefore that the frequency of occurrence of the strongest shears *across this layer* (surface–200-m) is greatest in the early hours of the morning and decreases with increasing solar elevation, the frequency of these shears would be expected to be slightly greater in the Shoeburyness sample where the ascent times were an hour or so earlier on average.

Résumé and concluding remarks. This study of vertical wind shear in the lowest layers at Shoeburyness and Larkhill is a limited study in several senses:

- (a) The measured shear is an *apparent* wind shear and not the true vertical shear of mean wind.
- (b) Only day-time shears are analysed.
- (c) Errors in computed shears across the surface–50-m layer at Shoeburyness are rather large.
- (d) The Shoeburyness/Larkhill comparison is restricted to the surface–200-m layer and to morning ascents only.

However, the object of the study was to extract as much information as possible about the climatology of the vertical wind shear in the lowest layers at

TABLE VII—LARGEST SHEARS IN VARIOUS NOMINAL LAYERS

Nominal layer	Layer thickness	S_{\max}	Root-mean-square error estimate
	<i>metres</i>		$m\ s^{-1}\ km^{-1}$
10-50	40	278	35
10-100	90	137	15
10-200	190	90	10
10-400	390	59	10
50-100	50	148	25
50-200	150	110	15
50-400	350	56	10
100-200	100	58	15
100-400	300	56	10
200-400	200	72	10

TABLE VIII—PERCENTAGE FREQUENCIES OF SHEAR MAGNITUDES IN VARIOUS NOMINAL LAYERS (SHOEBURYNES)

(a) All year, all directions, all times 0500-1800 GMT

Nominal layer	$S < 0$	$0 \leq S < 80\ m\ s^{-1}\ km^{-1}$	$S \geq 80\ m\ s^{-1}\ km^{-1}$	Total number of cases
<i>m</i>	<i>Percentage frequencies</i>			
10-50	8.1	70.9	21.0	1669
10-100	5.5	91.8	2.6	746
10-200	5.4	94.4	0.2	1311
10-400	4.3	95.7	0.0	1715
50-100	13.2	84.6	2.2	595
50-200	20.3	79.3	0.4	1231
50-400	14.7	85.3	0.0	1519
100-200	36.9	63.1	0.0	228
100-400	24.2	75.8	0.0	634
200-400	27.0	73.0	0.0	1160

(b) All year, directions 040-219°, all times 0500-1800 GMT

Nominal layer	$S < 0$	$0 \leq S < 80\ m\ s^{-1}\ km^{-1}$	$S \geq 80\ m\ s^{-1}\ km^{-1}$	Total number of cases
<i>m</i>	<i>Percentage frequencies</i>			
10-50	12.8	72.3	14.9	685
10-100	9.8	88.7	1.5	326
10-200	7.6	92.4	0.0	499
10-400	8.3	91.7	0.0	693
50-100	10.1	87.6	2.3	267
50-200	16.5	83.5	0.0	475
50-400	14.6	85.4	0.0	618
100-200	37.0	63.0	0.0	81
100-400	24.3	75.7	0.0	277
200-400	33.3	66.7	0.0	439

(c) All year, directions 220-039°, all times 0500-1800 GMT

Nominal layer	$S < 0$	$0 \leq S < 80\ m\ s^{-1}\ km^{-1}$	$S \geq 80\ m\ s^{-1}\ km^{-1}$	Total number of cases
<i>m</i>	<i>Percentage frequencies</i>			
10-50	4.7	69.9	25.4	984
10-100	2.2	94.5	3.3	420
10-200	4.0	95.8	0.2	812
10-400	1.6	98.4	0.0	1022
50-100	15.5	82.4	2.1	328
50-200	22.7	76.7	0.6	756
50-400	14.7	85.3	0.0	901
100-200	36.8	63.2	0.0	147
100-400	24.1	75.9	0.0	357
200-400	23.1	76.9	0.0	721

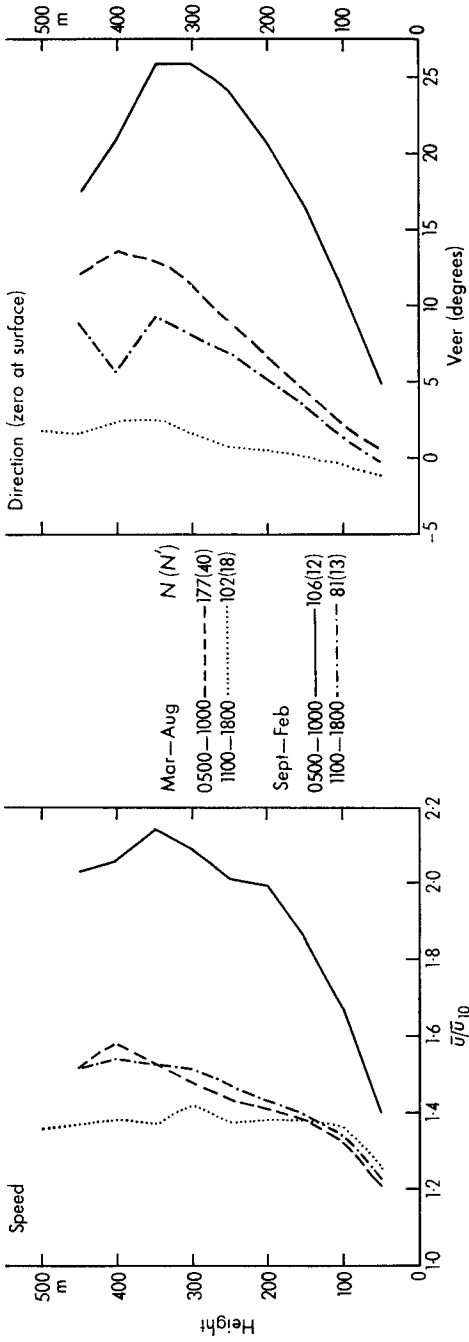


FIGURE 1—SHOEBURYNESS MEAN WIND PROFILES (1968-72)

(a) Surface wind direction 300-039 degrees. (N is the total number of cases sampled in the lowest levels up to 200 m and N' is the number sampled at the level where the profile terminated.)

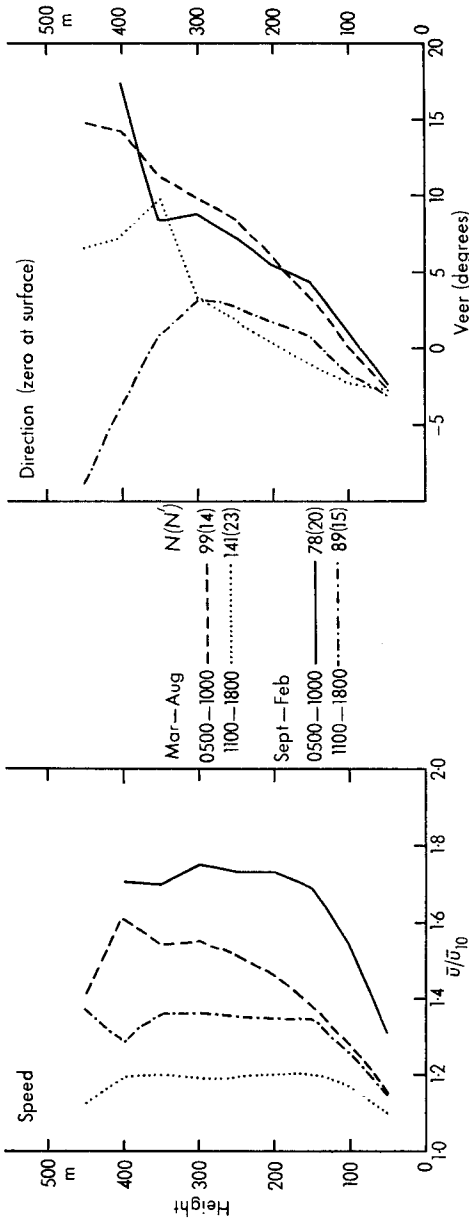


FIGURE 1—continued
(b) Surface wind direction 040-149 degrees. (For explanation of *N* and *N'* see notes under Figure 1 (a).)

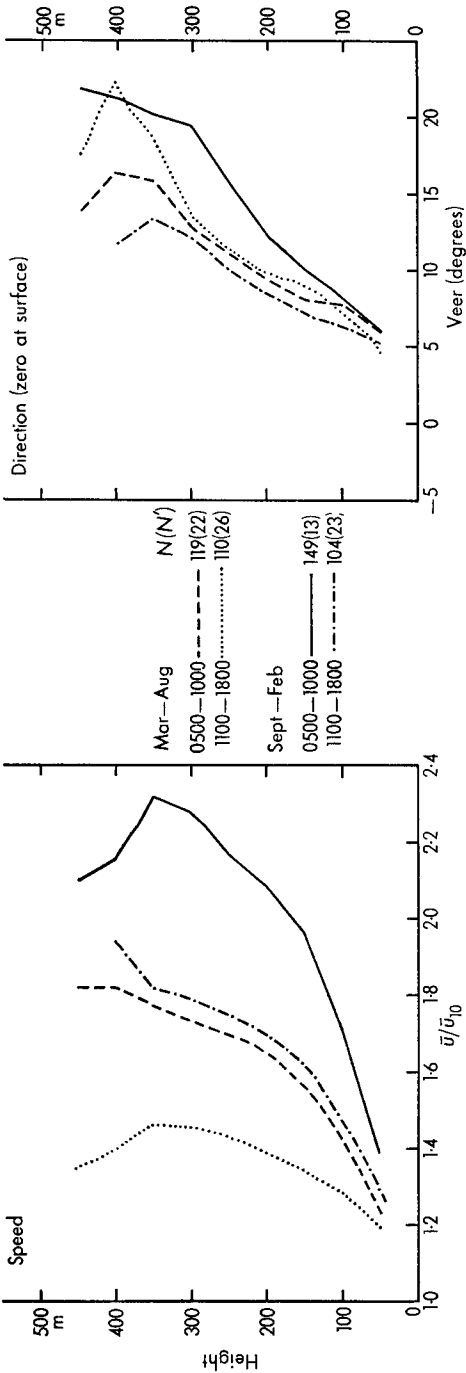


FIGURE 1—continued

(c) Surface wind direction 150-239 degrees. (For explanation of *N* and *N'* see notes under Figure 1 (a).)

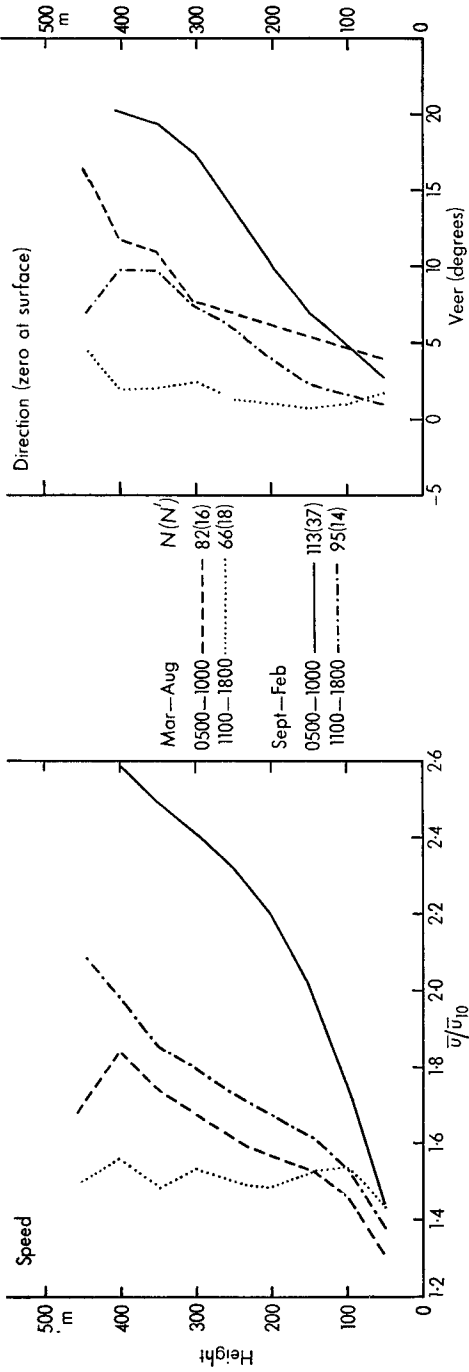


FIGURE 1—continued

(d) Surface wind direction 240–299 degrees. (For explanation of *N* and *N'* see notes under Figure 1 (a).)

TABLE IX—COMPARISON OF SHEARS IN THE SURFACE-200-m LAYER AT LARKHILL (0700-1000 GMT) AND SHOEBURYNNESS (0500-1000 GMT) (ALL SURFACE WIND DIRECTIONS INCLUDED)

Season	Site	$S < 20$ m s ⁻¹ km ⁻¹	$20 \leq S < 40$ m s ⁻¹ km ⁻¹	$S \geq 40$ m s ⁻¹ km ⁻¹	Total number of cases
Percentage frequencies					
(all year)	{ Larkhill	44.4	39.3	16.3	759
	{ Shoeburyness	40.4	38.5	20.2	749
Winter	{ Larkhill	15.9	48.4	35.7	182
	{ Shoeburyness	14.7	44.7	40.6	170
Spring	{ Larkhill	54.8	34.1	11.1	208
	{ Shoeburyness	49.5	36.1	14.4	205
Summer	{ Larkhill	70.4	26.5	3.1	196
	{ Shoeburyness	70.5	23.8	5.7	193
Autumn	{ Larkhill	32.4	50.3	17.3	173
	{ Shoeburyness	26.6	50.5	22.8	184

Shoeburyness and Larkhill from existing and readily available records of pilot-balloon soundings; although the limitations obviously necessitate some caution in the interpretation of the results, this object has been achieved.

Shoeburyness—surface-50-m layer. The largest day-time shears occurred most frequently in generally free-convective conditions with moderate to strong surface winds from directions in the range 210–330 degrees; 23 of the 29 largest shears (with $S \geq 160 \text{ m s}^{-1} \text{ km}^{-1}$) occurred with winds off the land. In winds originating over the sea the largest shears occurred almost exclusively in winter in the 0500–1000 period.

Overall, 21 per cent of shears exceeded $80 \text{ m s}^{-1} \text{ km}^{-1}$ (4.74 kt per 100 ft) and 1.7 per cent exceeded $160 \text{ m s}^{-1} \text{ km}^{-1}$ (9.47 kt per 100 ft); 1.2 per cent exceeded 10 kt per 100 ft.

For 'land' winds the frequency distribution of shears $\geq 80 \text{ m s}^{-1} \text{ km}^{-1}$ is in quite good agreement with that expected (except for $S \geq 180 \text{ m s}^{-1} \text{ km}^{-1}$), a normal intensity of turbulence in near-neutral conditions being assumed; for 'sea' winds, however, the predicted frequency of shears $\geq 120 \text{ m s}^{-1} \text{ km}^{-1}$ is only about a quarter of the observed frequency.

Shoeburyness—other layers. With winds off the land the maximum frequency of the biggest shears occurred in winter with the minimum in summer; with winds off the sea the maximum also occurred in winter but the minimum in autumn.

Shear magnitudes exceeded $80 \text{ m s}^{-1} \text{ km}^{-1}$ on 2.6 per cent of occasions across the surface-100-m layer, on 0.2 per cent of occasions across the surface-200-m layer, and on 2.2 per cent of occasions across the 50-100-m layer.

Larkhill/Shoeburyness comparison. The figures for the surface-200-m layer in the morning period show that there were consistently, in all four seasons, more of the larger shears (with $S \geq 40 \text{ m s}^{-1} \text{ km}^{-1}$) at Shoeburyness, although none of the differences are statistically significant. However, it is obvious that the nature of the wind-shear distribution for the surface-50-m layer is quite different from that for the surface-200-m layer and so it is not possible to draw firm conclusions about the relative incidence of large day-time shears in the lowest layer at Shoeburyness and Larkhill from the relative incidence in the surface-200-m layer.

General comparison of inland and coastal sites. The Shoeburyness results provide a basis for some qualitative speculation about the comparability of coastal and inland sites from the point of view of the incidence of excessive day-time vertical wind shear in the lowest 50 m (as measured by pilot-balloon soundings). Most of the largest shears occurred in generally free-convective conditions with moderate to strong surface winds off the land, and appear to be mostly attributable to the natural gustiness of the wind in these lowest layers. Over the year as a whole an inland site may be expected to have more excessive day-time shears than the coastal site on the simple basis that the generally greater roughness lengths (considering all directions) associated with an inland site imply larger mean shears and turbulence intensities. If the terrain at the inland site is similar to that to the west and north of Shoeburyness, then the overall frequency of large day-time shears would be expected to approximate to that for 'land' winds at Shoeburyness, assuming that the inland site has a similar synoptic experience. This conclusion probably does not apply to the winter months since Shoeburyness results show that most of the largest shears in the surface-50-m layer in winter are associated with winds off the sea.

The limitation of the observations to the period 0500-1800 prevents useful extension of the speculation to night-time shears.

Acknowledgements. Thanks are due to the Meteorological Office staffs at Shoeburyness and Larkhill for their much appreciated efforts in the collection of the data used in this report.

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FIFTH LONG ASHTON SYMPOSIUM ON ENVIRONMENTAL EFFECTS ON CROP PHYSIOLOGY, UNIVERSITY OF BRISTOL, 13-16 APRIL 1975

By MARJORY G. ROY

This international symposium was held at the University of Bristol to mark the retirement of Professor J. P. Hudson from Long Ashton Research Station. It attracted over 150 participants, many of whom were from overseas, and the residential nature of the arrangements at one of the Halls of Residence of the University encouraged some lively discussions, apart from those during the official sessions.

In his inaugural lecture on the evening of 13 April Professor Hudson posed the question whether enough was known about plant responses to weather and climate for action to be taken to even out the weather-induced year-to-year variations in yields of many crops (notably fruit crops) by breeding or appropriate cultivation techniques. It was suggested that even if reliable seasonal or longer-period forecasts were available the agricultural industry could not utilize them at present to improve yields.

The five sessions of the symposium were on 'Weather and Crop Productivity', 'Physiological Processes—Assimilate Production', 'Physiological Processes—Respiration and Translocation', 'Critical Stages of Plant Development', and 'Modelling the Synthesis of Results'. To agricultural meteorologists the papers presented in sessions I, IV and V were most closely related to problems which they might have to tackle, but the more technical papers in sessions II and III emphasized the problems of measuring plant response to the environment and the interpretation of the results obtained. The use of physical and biological models to simulate plant and crop response to weather and climate has highlighted the gaps in experimental and theoretical knowledge of the interactions between plants and the weather and there was some heated discussion of the usefulness of the model-building techniques in such a situation. It was generally agreed that although models could for instance provide realistic estimates of the build-up of dry matter in vegetative material, they did not as yet cope satisfactorily with phenological change in the crop (initiation and development of flowering, filling of storage organs such as grains etc.). These are of great significance for most agricultural and horticultural crops where the harvested yield (grains, roots, fruit etc.) is only a part of the total biomass.

Although some useful relations between yield and weather have been obtained using simple correlation techniques, it seems likely that further progress depends on greater understanding of the interactions of crops and weather at a more fundamental level. This symposium showed how much further basic research has to go before it becomes feasible to predict for any crop (or indeed variety of a single crop) the yield to be expected with a given set of weather conditions during the growing season. In the context of yield, the problem of dealing with plant diseases was mentioned and it was suggested that in many cases these were now the limiting factors in crop production.

The symposium was most efficiently organized by Drs J. J. Landsberg and C. V. Cutting and their team from Long Ashton, and the excellent chairing of the different sessions kept the discussion both lively and relevant.

REVIEWS

Review of urban climatology 1968–1973, WMO Technical Note No. 134, by T. R. Oke. 275 mm × 210 mm, pp. xviii + 132, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1974. Price: Sw.Fr.20.

Dr T. R. Oke, acting as a rapporteur on urban climatology for the WMO Commission for Special Applications of Meteorology and Climatology, has produced this review which documents the developments in the study of urban

climate since the Brussels Symposium on Urban Climates and Building Climatology in 1968, the proceedings of which were published by WMO as *Technical Notes* 108 and 109. The author's approach to this task is a sound one, since he arranges his review to deal separately with the basic physical processes which are of importance in the urban environment. In each of the three sections devoted to the balances of radiation, water and energy, he describes in essence the fundamental theoretical and observational problems which exist and discusses critically the attempts which have been made in recent years to tackle these problems.

The following section entitled 'Climatological Effects' is a collation of the results of observations of conventional climatological elements in and around urban areas. An indication of the development of interest in urban climatology is provided by a count of over 20 urban areas which were the subjects of published 'heat island' studies during 1972 alone.

The problems of airflow in and over cities provide a continuing challenge, and engineers concerned with the design of tall wind-sensitive structures are vocal in their demands for advice on wind profiles and characteristics of turbulence in the first few hundred metres above ground. The lack of uniformity of surface roughness in urban areas is obviously the main difficulty here, and estimates of roughness length for different cities vary widely, often because of unsatisfactory allowance for zero-plane displacement. Recent experimental attempts to study the wind field using balloons are reviewed. These have contributed to our knowledge of conditions in light or moderate winds, but profiles and turbulence in strong winds are obviously of most practical concern for the structural engineer.

The final section of the review is devoted to discussion of advances in numerical modelling of urban atmospheric conditions, which can be traced back to Gold's (1956) simple model which developed a sea-breeze type of circulation from initially calm conditions due to low-level temperature differences. At the end of this section, the outstanding problems in modelling are summarized and the desirable characteristics of a boundary-layer model for the study of the urban atmosphere are set out.

The extensive bibliography updates admirably the work of Chandler* and provides a useful starting-point for a newcomer to the field.

J. S. HOPKINS

Atmospheric diffusion—the dispersion of windborne material from industrial and other sources, by F. Pasquill. 225 mm × 150 mm, pp. xi + 429, illus., Ellis Horwood Ltd, Coll House, Westgate, Chichester, Sussex, 1974. Price: £16.

The first edition of Dr Pasquill's book *Atmospheric diffusion* requires no introduction to those seriously interested in or working on the topic. This second edition, although following the same general pattern as the first, is fully justified

* CHANDLER, T. J.; Selected bibliography on urban climate. Geneva, World Meteorological Organization, 1970.

in that the original material has been brought up to date and expanded as necessary and a greater emphasis has been placed on the practical applications of the concepts and techniques presented, something which will be appreciated by everyone actively involved in problems of effluent dispersal.

A brief, but well-balanced, introductory chapter is followed by three chapters dealing respectively with the relevant properties of atmospheric turbulence, theoretical representations of diffusion and observational aspects of the topic. Chapters 2 and 3 provide the reader with considerable insight into time and distance scales in relation to horizontal and vertical diffusion, the effects of stability and wind shear, and the range of applicability to gradient transfer, similarity- and statistical-theory treatments of diffusion, to name but the more important aspects discussed. Close attention is given to physical reality throughout and Chapter 4 complements this with a detailed discussion of the more important experimental studies of the basic features of atmospheric diffusion, providing the reader with an appreciation of the limitations of the theoretical descriptions of diffusion. The difficulties of obtaining the relevant data, particularly in the vertical, for validation of the theory are highlighted.

From the point of view of the person involved in the computation of the distribution of pollution emitted from real sources, the final two chapters (5 and 6) are the most important. Chapter 5 deals with various aspects of diffusion from real sources and includes sections on plume rise, pollutant removal mechanisms, effects of topography and buildings, pollution from urban areas (multiple sources) and long-range transport. Chapter 6 is intended to be self-contained and is aimed at the person who has to apply the techniques and theory (discussed in the previous chapters) to obtain estimates of the current or future distribution of a pollutant. On the whole the chapter meets its objective and gives the practitioner an excellent appreciation of the concepts involved and their practical implications. Considerable stress, and rightly so, is laid on the importance of departures from the idealized conditions assumed in the theoretical representations and on the relative sensitivity of the estimates to the assumptions and values of the parameters involved (for instance the correct specification of the plume spread is more important than the Gaussian assumption). Overall the material in this book is very well presented and clearly set out with apparently very few errors—I noticed just the one. Obscurities are rare, although the definition of stability at the beginning of Chapter 6 could prove confusing to some readers.

The person involved in making pollution estimates may be disappointed by the lack of positive recommendations in certain sections (for example on how to cope with specific topographical features and on the R & D areas which are likely to be the most fruitful in producing better estimating systems) and some sections (for example on urban pollution and on practical systems of calculating dispersion) show some imbalance. In these two sections perhaps not enough consideration is given to work carried out in the U.S.A. and elsewhere in comparison with that in the United Kingdom. However, relative to the quality of the book as a whole, these are mere quibbles. In conclusion one must unreservedly recommend this book to all who are involved in the theoretical or practical aspects of atmospheric diffusion.

NOTES AND NEWS

Retirement of Mr L. S. Clarkson

Mr L. S. Clarkson studied Physical Chemistry at Liverpool University and was awarded a B.Sc. degree with first class honours in 1936 and an M.Sc. in 1937. He joined the Meteorological Office in 1940 and during the early part of the Second World War he had several postings in the United Kingdom. In 1943 he joined the Royal Air Force Volunteer Reserve (Meteorological Branch) and served as a Flight Lieutenant at Headquarters No. 93 Group, in West Africa and at No. 4 Group. He was demobilized in August 1946 but continued to serve at No. 4 Group in the grade of Senior Scientific Officer. In 1947 he was posted to No. 21 Group and in 1951 to the Flying Training, Army and Ministry of Supply Branch of the Meteorological Office at the Headquarters in London. On promotion to Principal Scientific Officer in January 1954 he became Chief Meteorological Officer at Headquarters Far Eastern Air Force (Singapore) and he stayed there until mid 1957 when he was posted to London Airport (Heathrow) where he stayed for six years. In 1965 he again went overseas—this time to Cyprus. After his return to the United Kingdom late in 1966 he served at Uxbridge, the Instruments and Observations Branch (later known as the Operational Instrumentation Branch) and the Observational Requirements and Practices Branch. He was promoted there to Senior Principal Scientific Officer early in 1973 and became Assistant Director. He continued to serve in this capacity until his retirement in July 1975.

Mr Clarkson has had a varied career in a variety of places; throughout he has applied a single-minded purpose and shown a thorough approach to all his work. Work prepared by him or under his supervision has the stamp of painstaking, methodical and comprehensive preparation and he has consistently reached his decisions after careful consideration of the problems. When his mind was made up he would adhere to the view and defend his deductions and policy logically and strongly. In his latter years of work at Headquarters he was Chairman of some HQ Working Groups dealing with observational problems both of a conventional kind and those involving the use of weather radars. By his systematic and thorough approach to the several problems he has contributed significantly to the success of these Working Groups and has guided their deliberations well.

Mr and Mrs Clarkson will continue to reside near Chertsey. Their many friends and colleagues in the Meteorological Office will, I am sure, wish them both a long and happy retirement and hope that they both keep in good health to enjoy their sailing and other activities.

N. BRADBURY

Daily synoptic weather maps from the 1780s

In the *Meteorological Magazine* for February 1975 Mr. J. A. Kington* gave an account of the work being undertaken at the Climatic Research Unit of the University of East Anglia on the construction of daily synoptic charts for the

* KINGTON, J. A.; Daily synoptic weather maps from the 1780s: a research project of synoptic climatology. *Met Mag, London*, 104, 1975, pp. 33-52.

latter part of the eighteenth century, commencing with the year 1781. The first four years, 1781 to 1784, have now been microfilmed and a copy, on 35-millimetre film, is available for inspection in the National Meteorological Library, Bracknell. It is hoped that eventually at least 10 consecutive years will be completed and made available for public use in this manner.

Transliteration of Cyrillic alphabets

The Meteorological Office has decided that henceforward any transliteration from Cyrillic alphabets will be made according to the joint system of the British Permanent Committee on Geographical Names (PCGN) and the U.S. Board on Geographic Names (BGN); this will apply to the cataloguing work of the National Meteorological Library at Headquarters, Bracknell and to references and bibliographies contained in Meteorological Office publications. The languages involved include Russian, Bulgarian, Ukrainian, White Russian and Serbian. This decision, which came into force on 1 June 1975, implies a reversion to the practice obtaining before 1959 at which time the Meteorological Office adopted the ISO/R9 system in order to be in line with a recommendation made by the World Meteorological Organization; however, the hoped-for international unanimity in the use of ISO/R9 never came about, and the large number of diacritical signs employed in this system make it unsuitable for computerized catalogues.

The BGN/PCGN system is described in the following publication: *Romanization Guide*, U.S. Board on Geographic Names, Washington, 1972.

CORRECTIONS

Meteorological Magazine, June 1975, p. 157, third and fourth lines from bottom of page. The equation should read:

$$\mathbf{V}_g = - \frac{1}{\rho f} \nabla p \times \mathbf{x}$$

and in the next line the κ should be in bold type.

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NOTICES

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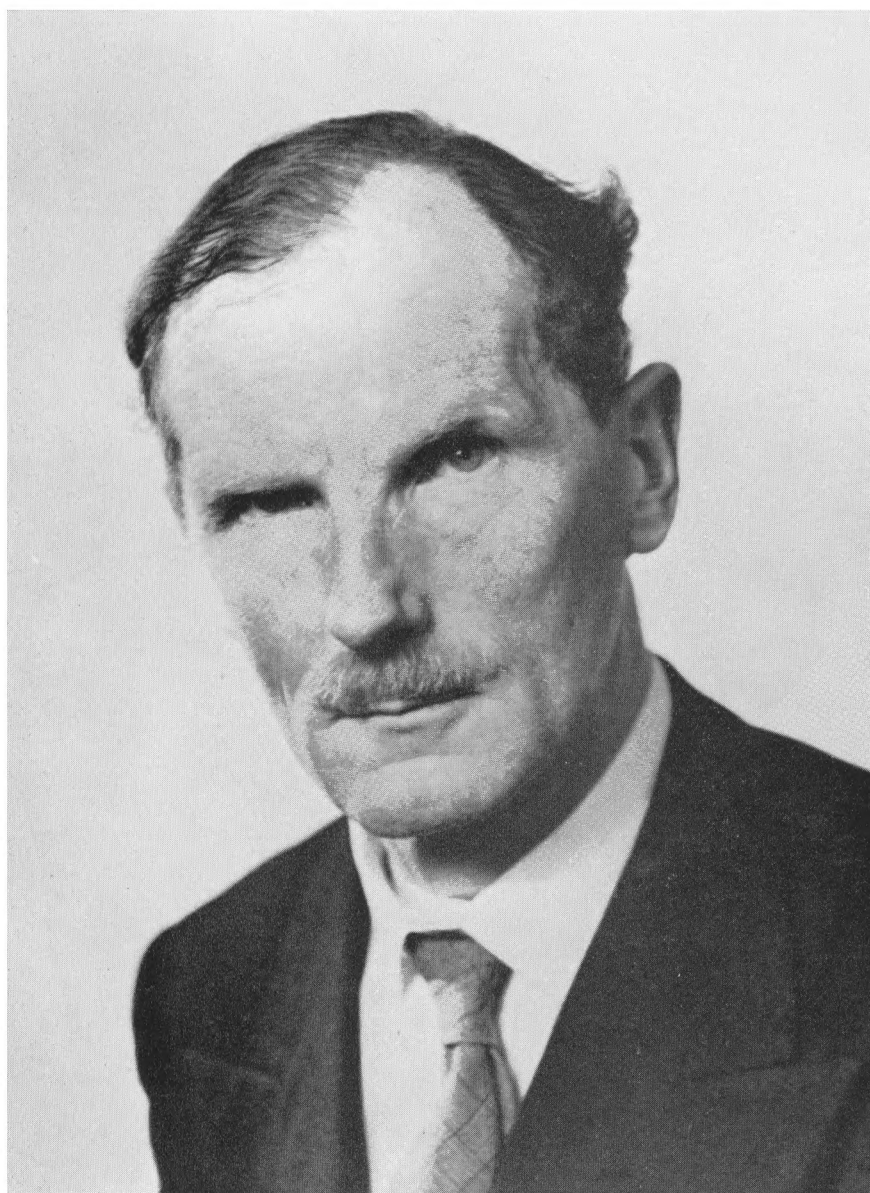
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OCTOBER 1975 No 1239 Vol 104

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DR J. M. STAGG, C.B., O.B.E., F.R.S.E.

THE METEOROLOGICAL MAGAZINE

Vol. 104, No. 1239, October, 1975

DR J. M. STAGG, C.B., O.B.E., F.R.S.E.

Dr James Martin Stagg, C.B., O.B.E., F.R.S.E., died on 23 June 1975, aged 74 years, at his home at Seaford, Sussex. He will be remembered by scientist and non-scientist for different reasons.

Dr Stagg was educated in Edinburgh at Broughton School and afterwards at the University. Following two years as a science master at George Heriot's School in the same city he joined the Meteorological Office in 1924. During his first eight years with the Office his postings were all to stations which were concerned with geophysical work and in 1932 he was selected to lead the British Polar Year Expedition to Fort Rae in Canada. The work of this expedition covered a wide range of geophysical studies and confirmed Dr Stagg as an ardent geophysicist. On release from the Polar Year duties he was posted back to Edinburgh for two years after which came the inevitable overseas posting for two years followed by a move to Kew Observatory in the spring of 1939. During the greater part of these 15 years he produced a steady flow of papers on geophysical subjects and he seemed set for a career in very congenial work.

Shortly after the outbreak of the Second World War Dr Stagg was transferred to an administrative post at headquarters where, for four years, he played his part in promoting the war effort of the Meteorological Office.

In the autumn of 1943 Dr Stagg learned with surprise that he was to be appointed as Chief Meteorological Adviser to the invasion planning staff. His work during the next seven months or so, culminating in the meteorological forecast for the actual invasion, is fully described in his own book—*Forecast for Overlord*. Throughout that account his integrity and force of character stands out. For the time he had to drop the scientific work which was his first love and deal with vitally urgent and important problems in which human relationships were some of the most important variables. His success in this field is now a matter for the history books and for many will constitute his claim to fame.

After the war and a further short period at Kew Observatory Dr Stagg was made Principal Deputy Director and later Director of Services. This was the start of the last phase of his work in the Office. During this period the operational side of the Office was developed both for aviation and for non-aviation users. The success which attended this post-war development on the operational side was due in no small measure to the character and ability of the man who directed it. Despite this preoccupation with operational meteorology he found

time to continue his geophysical work. From 1946 to 1951 Dr Stagg was General Secretary of the International Union of Geodesy and Geophysics and subsequently a member of the Finance Committee. He was elected President of the Royal Meteorological Society in 1959 and retired from the Office in 1960. After his retirement he maintained his interest in geophysical work and continued to serve on a number of national committees.

The marks of distinction awarded to Dr Stagg are a fitting commentary on his tripartite career. They were: O.B.E. (1937), Officer of the Legion of Merit conferred by the President of the United States of America (1945), C.B. (1954), Gauss-Weber Medal awarded by the Academy of Science, Göttingen (1955). Above all, he was a man of integrity who always fought hard for what he believed to be right.

A. C. BEST

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THE QUASI-BIENNIAL OSCILLATION AND ITS ASSOCIATION WITH TROPOSPHERIC CIRCULATION PATTERNS

By R. A. EBDON

Summary. Mean tropospheric circulation patterns for the northern hemisphere are examined for mid-season months when the phase of the equatorial stratospheric winds is either strong easterly or westerly. The results indicate significant differences particularly in January and July and suggest that the quasi-biennial oscillation in equatorial stratospheric winds may be an important feature in determining the character of the tropospheric circulation in middle and high latitudes.

Introduction. About 15 years ago attention was drawn to the fact that stratospheric winds over the equator showed considerable year-to-year variability with strong easterlies in one year being followed by strong westerlies in the following year.¹ This periodic fluctuation became known as the 'quasi-biennial oscillation' (QBO) and as more data became available and as interest in it developed a large number of papers appeared describing the behaviour of the QBO,^{2,3} its possible causes,^{4,5} and its role as a component part of the general circulation⁶ apparently capable of influencing developments away from the equatorial region in both the stratosphere^{7,8} and the troposphere.⁹

Long before wind and temperature data for the stratosphere became available various workers had detected periodicities of a biennial nature in tropospheric parameters¹⁰ and, in recent years, it has been suggested that these may be correlated with the QBO.¹¹

If such a relationship exists then it would be an important consideration in modelling the general circulation and also in the preparation of monthly and seasonal forecasts as it is usually a relatively simple matter to extrapolate for a few months ahead from the graph of 30-mb monthly mean zonal wind components near the equator (Figure 1).

In this paper the mean surface pressure patterns for the mid-season months (January, April, July and October) are examined to see if they show any

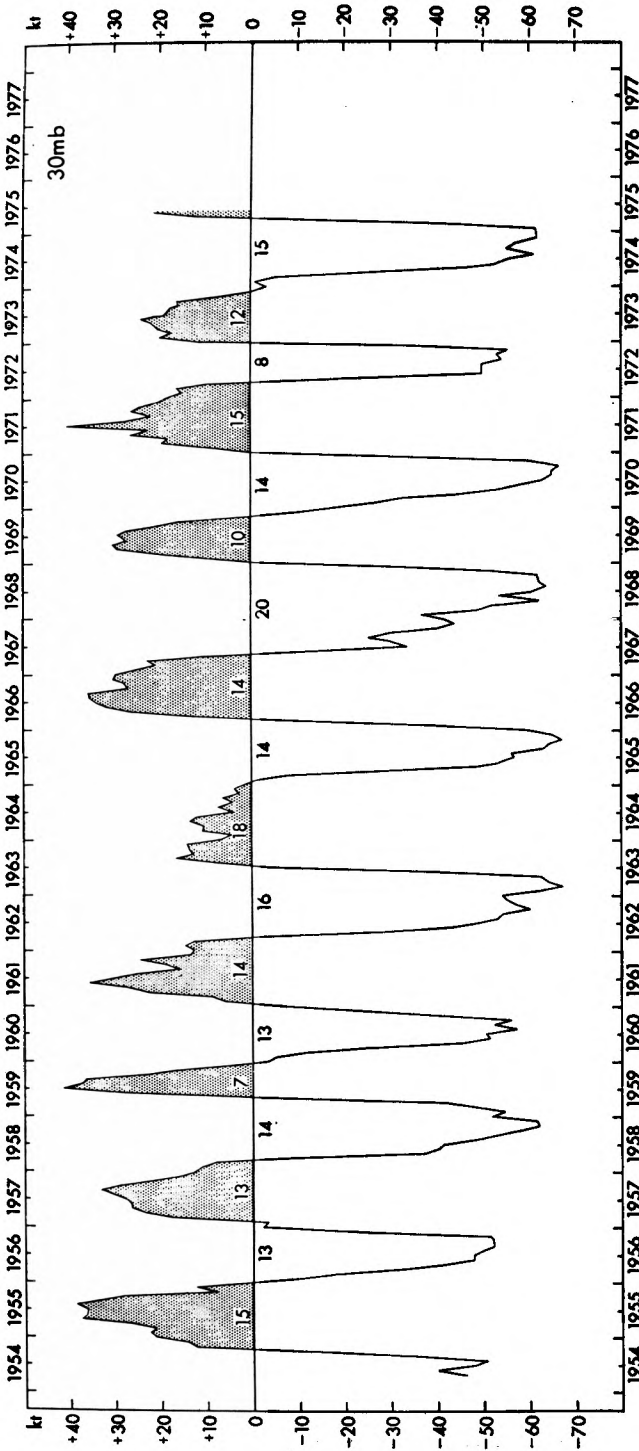


FIGURE 1—30-mb MONTHLY MEAN ZONAL WIND COMPONENTS AT CANTON ISLAND/GAN

Components towards the east are positive and stippled. Figures along the zero line indicate the duration, in months, of westerlies or of easterlies.

significant differences when the phase of the QBO (as measured by the 30-mb monthly mean zonal wind component over the equator) is either strong easterly or strong westerly.

Earlier work² has shown that the QBO appears to be in the same phase all around the equator and so the monthly mean 30-mb wind speeds quoted in the text, although for Canton Island or Gan only, may be taken as representative of speeds elsewhere close to the equator.

January. During the period July 1954 to July 1974 there were five Januaries when the phase of the QBO was such that the zonal wind component was a strong, or relatively strong, easterly. These were 1959 (52 knots), 1963 (54 knots), 1966 (60 knots), 1968 (38 knots) and 1970 (21 knots). Mean surface-pressure and 500-mb contour height charts were produced based on these five Januaries and the anomalies of the mean surface-pressure charts from the 1951–70 average, which are broadly similar to those at 500 mb, are shown in Figure 2.

The Januaries when the phase of the QBO was markedly westerly were in 1955 (21 knots), 1958 (13 knots), 1962 (13 knots), 1967 (29 knots) and 1972

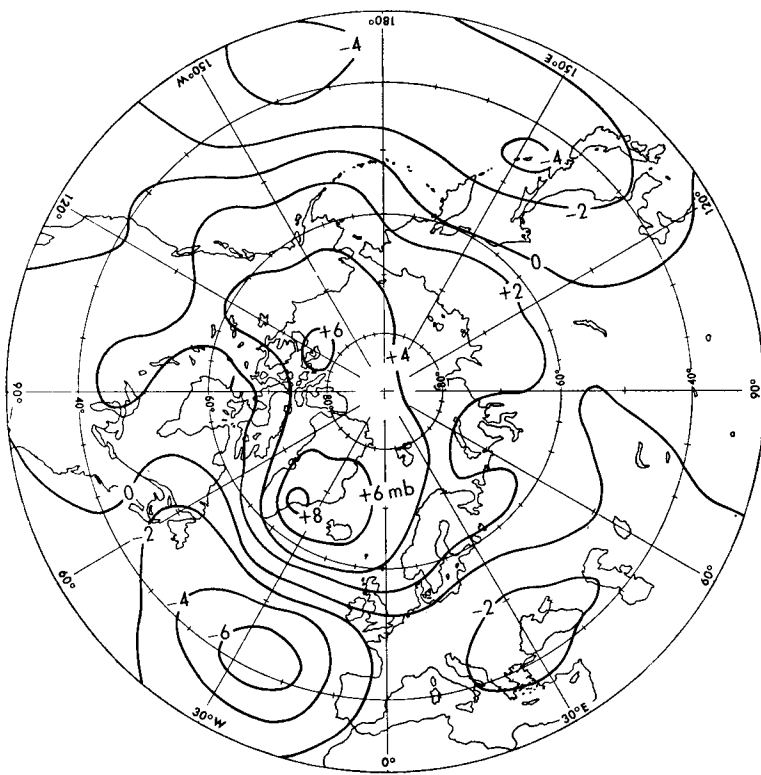


FIGURE 2—SURFACE PRESSURE ANOMALY FROM 1951–70 AVERAGE, JANUARY

Mean of five Januaries with easterly phase of QBO at 30 mb.

(18 knots). The anomalies, from the 1951–70 average, of the mean surface pressure based on these five months are shown in Figure 3. Corresponding 500-mb anomalies are similar.

The charts in Figures 2 and 3 show that there are considerable differences between the two sets of years. With a strong easterly phase of the QBO at 30 mb (Figure 2) the surface pressure chart shows a large area of positive anomalies in high latitudes with an almost continuous ring of negative anomalies in middle latitudes. When the QBO is in the opposite phase then Figure 3 shows an almost complete reversal of the surface pressure anomaly pattern. In high latitudes negative anomalies prevail and there is an almost complete ring of positive anomalies in middle latitudes.

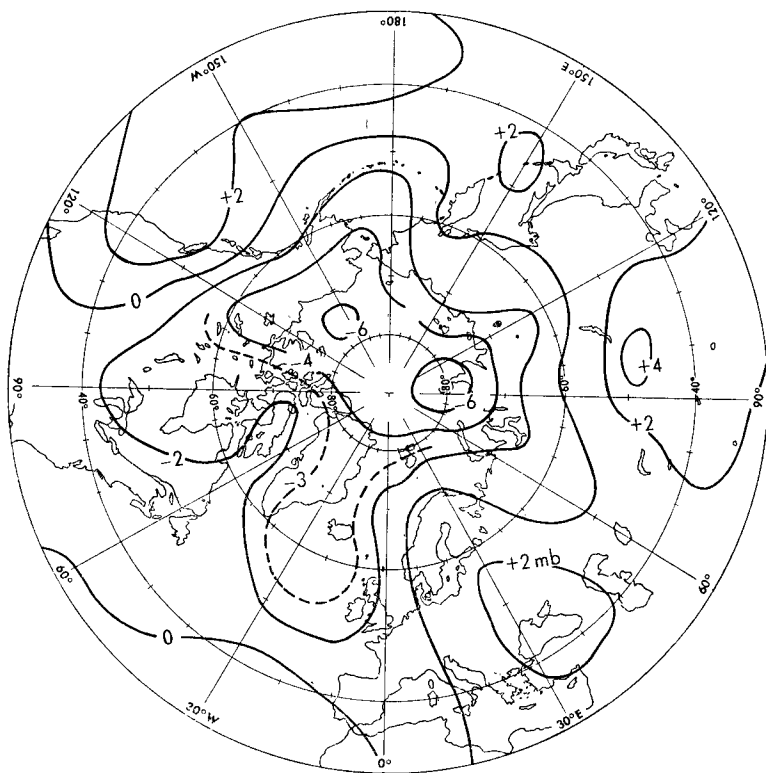


FIGURE 3—SURFACE PRESSURE ANOMALY FROM 1951–70 AVERAGE, JANUARY

Mean of five Januaries with westerly phase of QBO at 30 mb.

The mean surface pressure charts for the two sets of years show that during the easterly phase of the QBO positive anomalies in high latitudes lead to a separate high centre over the Canadian Arctic and a marked increase in the easterly gradient over north-east Siberia and Alaska. In the Atlantic sector the patterns differ very considerably. During the westerly phase of the QBO the Iceland low is apparently close to the 1951–70 average position but the mean pressure at the centre is a little lower, while the Azores high is close

to its usual latitude with pressures marginally above average. This results in a very marked increase in the westerly gradient over the central North Atlantic and north-west Europe. On the other hand, the mean surface pressure chart based on those Januarys when the QBO was easterly shows the Iceland low to be displaced about 5 to 10 degrees of latitude south of the 1951-70 average position, with pressure gradients across the central North Atlantic and north-west Europe much weaker than average. In addition, the troughing over eastern Europe to the eastern Mediterranean is very pronounced.

The differences between the two sets of January charts were tested for significance using the program written for Welch's test as described by Ratcliffe¹² and the areas in which the averages differ significantly are shown in Figure 4. The total number of significant points over the hemisphere north of 35°N (but excluding the North Pacific south of 50°N owing to the paucity of data) was 90 for surface pressure and 52 for 500-mb heights. These values probably indicate significance at greater than the 1 per cent level though the exact value is in doubt due to the relatively small sample size (5 years only).

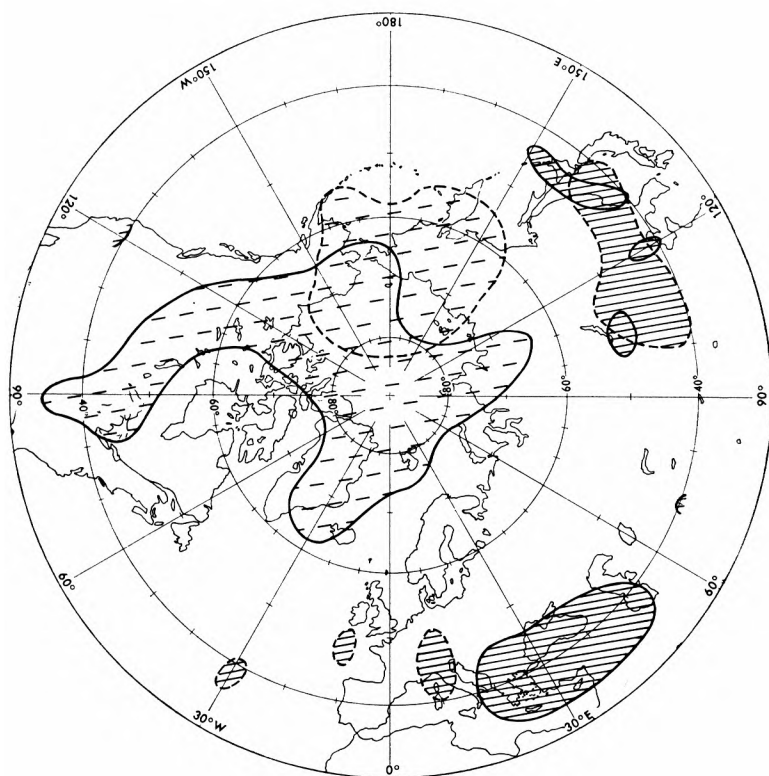


FIGURE 4—AREAS WHERE MEAN SURFACE PRESSURES AND 500-mb CONTOUR HEIGHTS WERE SIGNIFICANTLY DIFFERENT DURING WESTERLY AND EASTERLY PHASES OF THE QBO AT 30 mb IN JANUARY

——— Surface pressure - - - - - 500-mb height

Hatched areas denote areas of positive anomaly; dashed areas denote negative anomaly.

In view of the suggestion that these very large differences in the lower tropospheric patterns might be attributable in some way to the phase of the QBO in equatorial stratospheric winds, cross-sections of zonal wind component along 80°W were prepared to see if the data indicated a possible relationship between the stratosphere in high and low latitudes and/or between the stratosphere and the troposphere. The reason for selecting 80°W is that, near this longitude, upper-air stations with monthly mean data to 30 mb or above are more plentiful than over other parts of the hemisphere and, for recent years, are readily available from *Monthly Climatic Data for the World*.¹³ From Figures 2 and 3 it is apparent that similar cross-sections at other longitudes might prove more interesting if the necessary data were available.

Mean cross-sections were prepared using data for January 1967, 1972 and 1973 as representative of the westerly phase of the QBO and for January 1966, 1968 and 1970 as representative of the easterly phase. The cross-section showing the difference between these two is at Figure 5. It should be noted that the months were selected on the criterion of the phase of the QBO at 30 mb and, in some of the months the zonal wind component was of opposite sign at other stratospheric levels. From this analysis it appears that when the phase of the

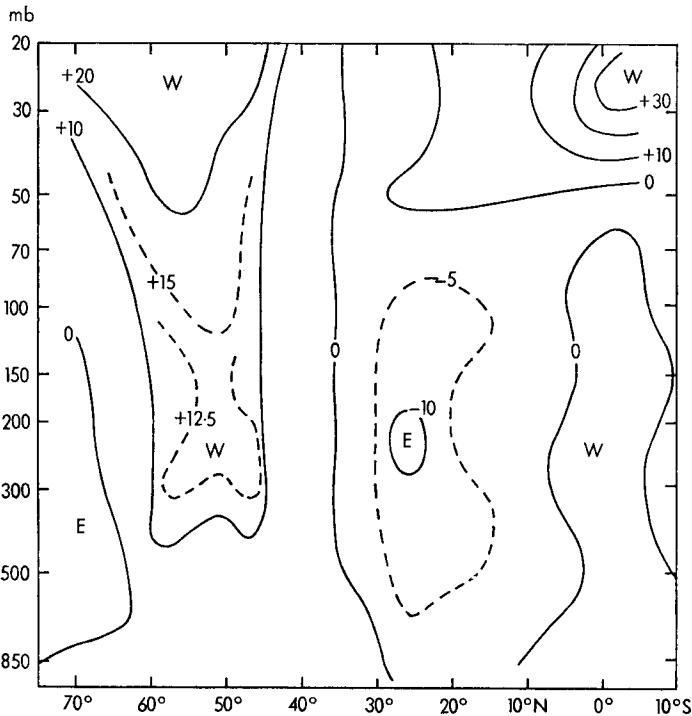


FIGURE 5—VERTICAL CROSS-SECTION AT 80°W SHOWING DIFFERENCES BETWEEN ZONAL COMPONENT DURING WESTERLY AND EASTERLY PHASES OF THE QBO AT 30 mb IN JANUARY

Speeds are in metres/second.

QBO is westerly at 30 mb then, over middle and high latitudes, the westerly circulation is stronger than in the easterly phase of the QBO—at least at 80°W—at the 30-mb level.

An examination of the 30-mb monthly mean charts for the six Januarys used shows that, in general terms, this statement can be extended to cover a large part of the hemisphere. In the three Januarys 1967, 1972 and 1973 (all with westerly phase of the QBO at 30 mb) the monthly mean 30-mb contour charts showed a very strong winter circulation and in each month the heights at the centre of the vortex were below 22.0 km. In the other three Januarys (1966, 1968 and 1970) the monthly mean 30-mb patterns were more variable—in 1966 the lowest heights were probably about 22.2 km, in 1968 about 23.0 km and in 1970 about 22.7 km. These three Januarys (coinciding with a pronounced easterly phase of the QBO at 30 mb) certainly appear to have a weaker westerly flow over high latitudes. In using these stratospheric charts it must, of course, be borne in mind that the sample (only three in each set) is far too small to enable one to draw reliable conclusions. Nevertheless it is interesting to speculate as to whether or not the polar night stratospheric jet in January is stronger because the QBO is in a westerly phase and weaker because it is in an easterly phase. However, if such a relationship does exist, a much longer period of data will be needed before it can be shown with any degree of confidence.

Another interesting feature of the cross-section in Figure 5 is the suggestion that the enhanced westerly flow in the stratosphere appears to be associated with stronger westerlies in the troposphere with a secondary maximum between 300 and 200 mb at about 45 to 55°N. Certainly the chart in Figure 3 indicates that enhanced surface westerly flow occurs over most of the hemisphere north of about 50°N when the phase of the QBO at 30 mb is westerly.

This enhanced westerly flow was also apparent on the corresponding 500-mb charts and, in order to examine whether or not the mean latitude of the maximum flow at 500 mb does vary significantly between these two sets of Januarys, the monthly mean wind speeds at 500 mb were calculated and averaged around latitude circles. The mean speeds were obtained by using daily 500-mb height grid-point values with a spacing of 5 degrees latitude and 10 degrees longitude to calculate the zonal (u) and meridional (v) components. The speed was then derived from $(u^2 + v^2)^{1/2}$. The monthly mean values around the latitude circles at 5-degree intervals from 60 to 30°N and also the five-year means (Figure 6) show that, over the hemisphere as a whole, when the phase of the QBO is westerly the average latitude of the strongest flow is about 35°N with individual Januarys varying between 35 and 45°N (1958 is an exception although in that January, there is a weak secondary maximum at 50°). During those Januarys when the phase of the QBO is easterly the monthly mean latitude of the maximum flow is farther south and varies between 30 and 40°N with a five-year mean of 30°N.

Reference was made earlier to the considerable differences in the Atlantic sector and these are confirmed by the mean 500-mb wind speeds along latitude circles from 60 to 30°N between 60°W and the Greenwich meridian (Figure 7). The five-year means show that during the easterly phase of the QBO the latitude of the maximum wind speed is about 35°N whilst the mean during the westerly phase is about 45°N. The curves for the individual Januarys show that when the QBO is easterly there is only one month (1968) when the

maximum is north of 40°N and that with the westerly phase there is only one month (1955) when the maximum is south of 40°N . This diagram also shows the enhanced westerly flow which accompanies the westerly phase of the QBO.

The central England temperatures and the England and Wales rainfall and sunshine data for these Januarys were examined but, despite the differences in tropospheric circulation patterns, there were no significant differences between the two sets of five years.

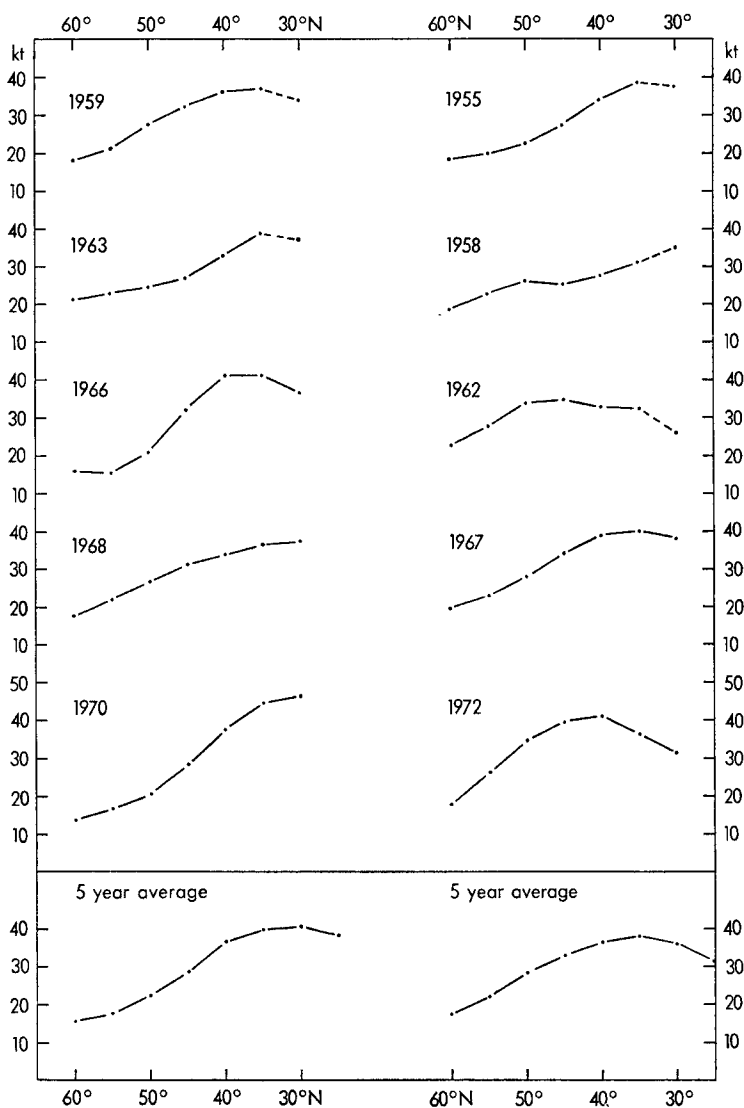


FIGURE 6—LATITUDINAL MEAN WIND SPEED AT 500 mb IN JANUARY

(a) Januarys with easterly phase of QBO at 30 mb,
 (b) Januarys with westerly phase of QBO at 30 mb.
 Wind speeds are in knots.

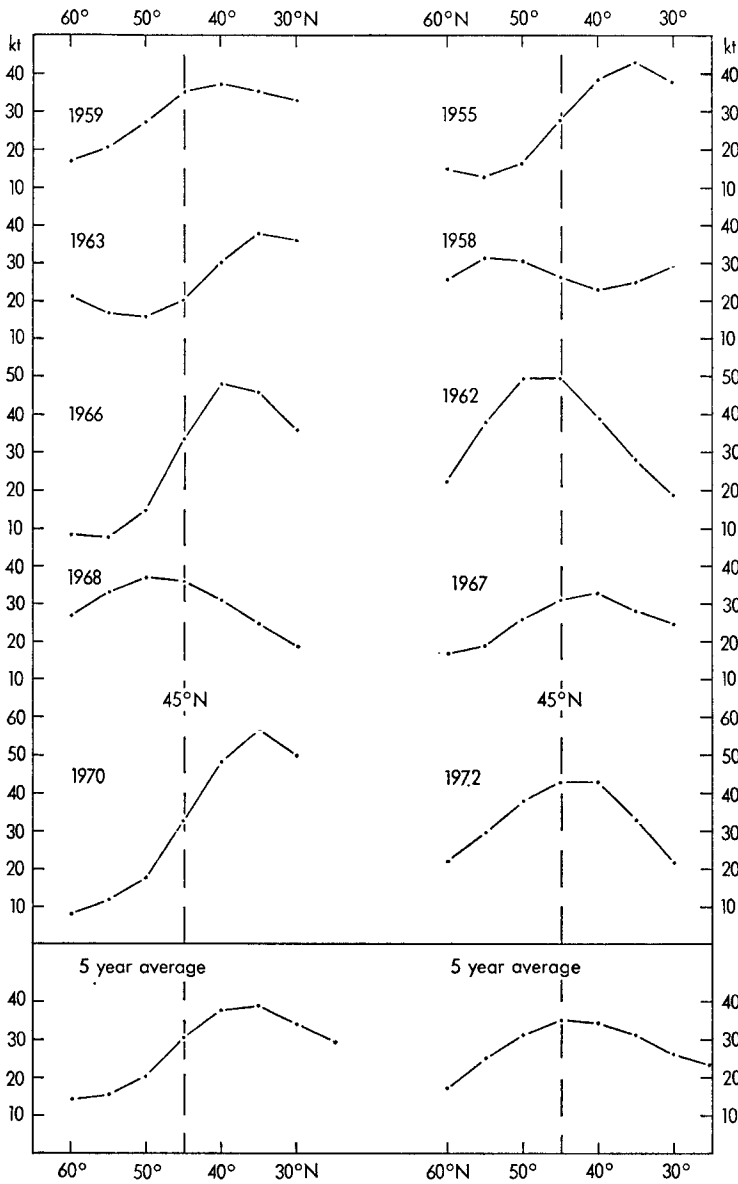


FIGURE 7—500-mb WIND SPEEDS MEANED ALONG LATITUDE CIRCLES OVER THE ATLANTIC FROM 60°W TO 0°, JANUARY

- (a) Januarys with easterly phase of QBO at 30 mb,
 (b) Januarys with westerly phase of QBO at 30 mb.
 Wind speeds are in knots.

July. Sets of mean pressure and 500-mb contour height charts were produced for the eight Julys when the QBO was in a strong easterly phase. The years were 1954 (48 knots), 1956 (48 knots), 1960 (51 knots), 1962 (49 knots), 1965 (57 knots), 1968 (60 knots), 1970 (62 knots) and 1972 (50 knots). Similar charts were also produced for the eight Julys when the QBO was strong westerly and these were 1955 (36 knots), 1957 (27 knots), 1959 (41 knots), 1961 (30 knots), 1966 (34 knots), 1969 (28 knots), 1971 (40 knots) and 1973 (19 knots). The anomalies of surface pressure of these sets of eight-year-mean charts from the 1951–70 average are shown in Figures 8 and 9. The anomalies are much smaller than those for January but this is not surprising in view of the large differences in standard deviation between the two months. However, there are areas where the difference between the average charts for the two sets of Julys are statistically significant and these are shown in Figure 10. The number of significant points in July (48 for surface pressure and 31 for 500-mb contour height) is less than in January but, using Welch's test these are significant at the 1 per cent level for surface pressure and between the 5 per cent and 10 per cent levels for 500-mb height.

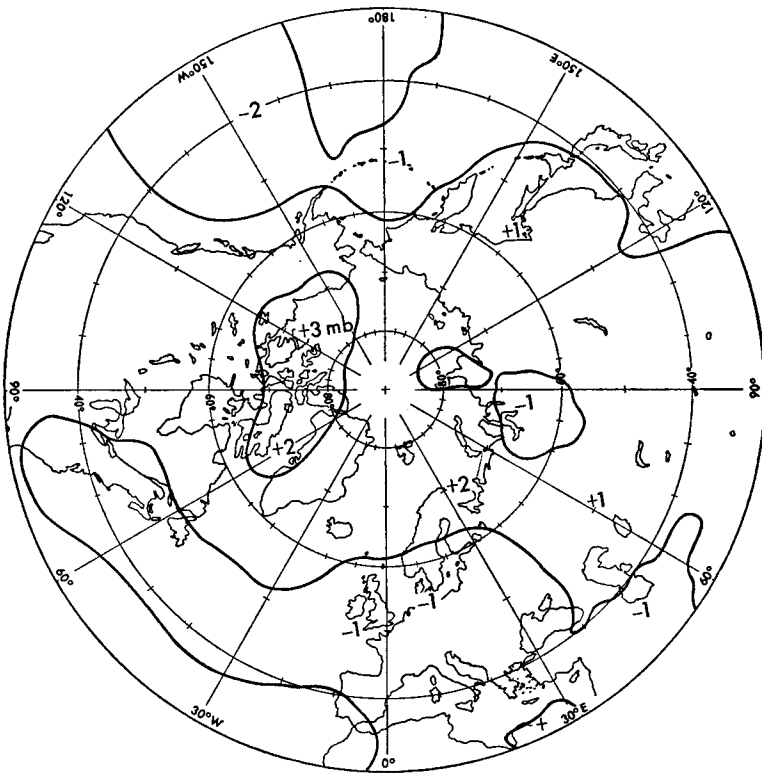


FIGURE 8—SURFACE PRESSURE ANOMALY FROM 1951–70 AVERAGE, JULY

Mean of eight Julys with easterly phase of QBO at 30 mb.

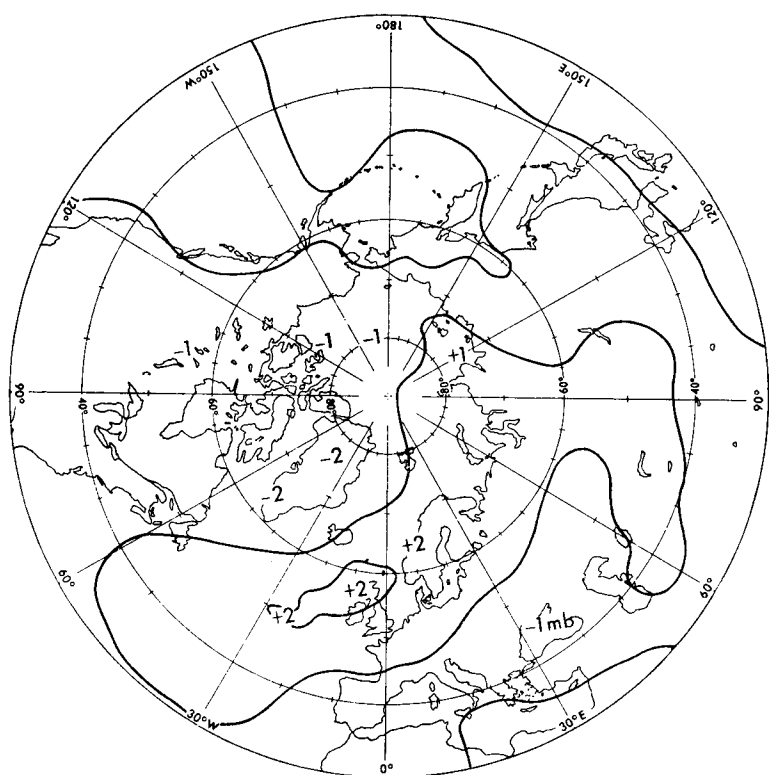


FIGURE 9—SURFACE PRESSURE ANOMALY FROM 1951-70 AVERAGE, JULY

Mean of eight Julys with westerly phase of QBO at 30 mb.

In July, as in the case of January, there is a suggestion that the mean charts based on the years when the QBO was easterly have surface pressures above average in high latitudes. Areas of particular interest are those around the British Isles, where the anomaly is negative, and northern Canada, where the anomaly is positive on the mean chart during the easterly phase of the QBO (Figure 8) changing to anomalies of opposite sign on the mean charts during the westerly phase of the QBO (Figure 9).

The cross-section of zonal wind components at 80°W (Figure 11) shows the differences between the easterly and westerly phases of the QBO at 30 mb (July, 1965, 1968, 1970 and 1972 representing the easterly phase and July 1966, 1969, 1971 and 1973 representing the westerly phase). At the 30-mb level, at 80°W the differences are very small outside the tropics and, in the troposphere, the only noticeable difference is the weak maximum at 250 to 150 mb near 40-45°N which suggests that the westerlies there might be a little stronger during the westerly phase of the QBO.

The mean charts based on the two sets of eight Julys show that the differences are such that the average position of the ridge extending north-eastwards from the Azores anticyclone is about 5 degrees of latitude farther north in those years when the phase of the QBO at 30 mb is westerly.

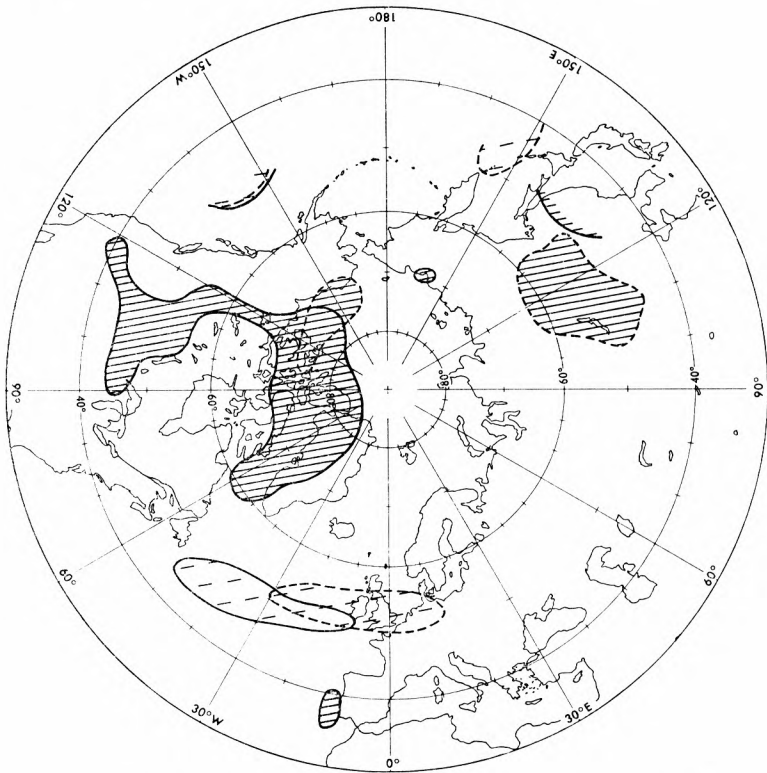


FIGURE 10—AREAS WHERE MEAN SURFACE PRESSURES AND 500-mb CONTOUR HEIGHTS WERE SIGNIFICANTLY DIFFERENT DURING WESTERLY AND EASTERLY PHASES OF THE QBO AT 30 mb IN JULY

—— Surface pressure - - - - 500-mb height
Hatched areas denote areas of positive anomaly; dashed areas denote negative anomaly.

The 500-mb wind speeds meaned around latitude circles over the whole hemisphere show little or no difference in the latitude of the strongest flow between the two sets of Julys. In both cases the maximum flow appears to be at 45°N. The eight-year mean values for the Atlantic sector (60°W to the Greenwich meridian) are shown in Figure 12 and, although in both cases the maximum is at 50°N, it can be seen from the curves that during the easterly phase of the QBO the maximum occurs between 45 and 50°N whereas during the westerly phase it occurs between 50 and 55°N. The individual monthly mean curves show that during the westerly phase all the maxima are near or north of 50°N whereas during the easterly phase four of the maxima occur at or south of 45°N and only one (1972) is north of 50°N. This is in agreement with the January result that during the westerly phase of the QBO the strongest flow at 500 mb is farther north than during the easterly phase. The differences between the two sets of years are reflected in the July temperatures for central England and the sunshine values for England and Wales.

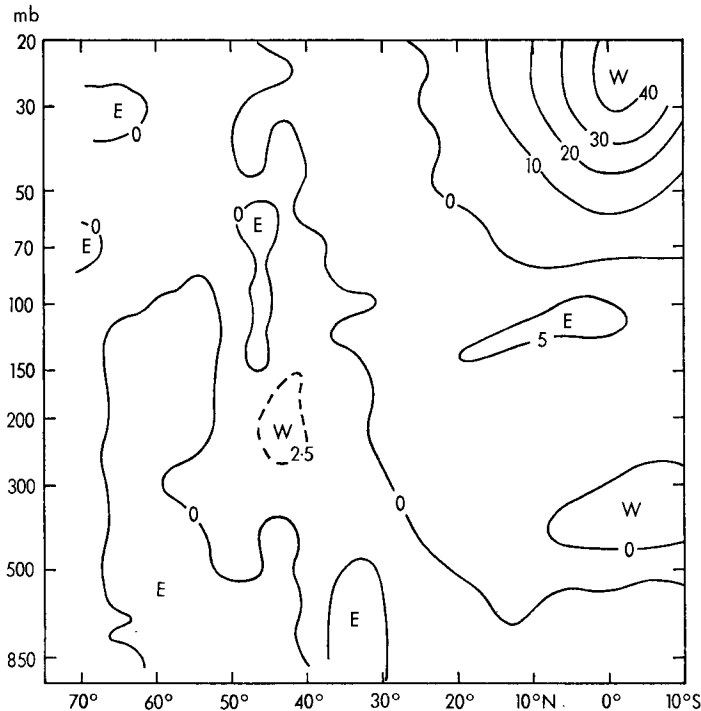


FIGURE 11—VERTICAL CROSS-SECTION AT 80°W SHOWING DIFFERENCES BETWEEN ZONAL COMPONENT DURING WESTERLY AND EASTERLY PHASES OF THE QBO AT 30 mb IN JULY

Speeds are in metres/second.

From Table I it can be seen that in the nine Julys, including 1974, when the phase of the QBO was easterly, seven of the monthly mean temperatures were in quintiles 1 and 2 and in the eight Julys when the phase was westerly five of the months were in quintiles 4 and 5.

The sunshine totals for the same Julys show that during the easterly phase of the QBO all nine years fell in tercile 1. The sunshine totals for the Julys associated with the westerly phase of the QBO are equally divided between terciles 1 and 3.

TABLE I—TEMPERATURES FOR CENTRAL ENGLAND AND SUNSHINE FOR ENGLAND AND WALES FOR JULYS, REFLECTING THE DIFFERENCES BETWEEN EASTERLY AND WESTERLY PHASES OF THE QBO

(a) Central England Temperatures (quintiles)								
Phase of QBO at 30 mb				1	2	3	4	5
Easterly	..	..	..	5	2	2	0	0
Westerly	..	..	..	1	1	1	3	2
(b) Sunshine for England and Wales (terciles)								
Phase of QBO at 30 mb				1	2	3		
Easterly	..	..	..	9	0	0		
Westerly	..	..	..	4	0	4		

Papers have been published suggesting that the summer weather over some parts of the northern hemisphere^{14,15} and, in particular, southern England¹⁶ may be associated with the behaviour of the stratosphere in high latitudes in spring. Table II summarizes this by showing the relationship between the summer index at Kew (as defined by Poulter¹⁷) and the date of the spring reversal (from winter westerly to summer easterly) of 30-mb zonal-wind components at Shanwell.

TABLE II—RELATIONSHIP BETWEEN SPRING REVERSAL OF 30-mb WINDS AT SHANWELL AND INDEX OF THE FOLLOWING SUMMER AT KEW, 1958–74

Time of spring reversal					Kew Summer Index	
					689–671	≤670
					≥690	
Late	..	..	..	0	2	5
Average	..	..	..	2	0	1
Early	..	..	..	5	2	0

A point of interest from this table is that, following an early change-over there has, so far, not been an outstandingly poor summer (June, July and August) and the only two summers which were average were 1972 and 1974. Although the spring wind reversal at 30 mb occurred early in both 1972 and 1974 these were years when the phase of the QBO was strong easterly and the inference from Table I would be for a cool and cloudy July. If the two very pronounced stratospheric events—the breakdown of the stratospheric winter polar vortex and the phase of the QBO in equatorial stratospheric winds—do influence the weather at the surface it may well be that they both make their separate contribution and that the indication from one of them should be modified to take account of the indication from the other.

April and October. Similar sets of charts were prepared for April (seven months in each sample) and October (eight months in each sample). In both cases there were relatively few grid points at which the differences were significant. An examination of the temperature, rainfall and sunshine values for the months used did not indicate any preference for warm or cold, dry or wet, sunny or cloudy Aprils or Octobers to occur over England and Wales more frequently with one phase of the QBO than with the other.

Conclusion. The results from this study are necessarily somewhat tentative in view of the fact that adequate stratospheric data are available for only a limited period. Nevertheless, the charts produced here support the view that the complete reversal of winds in the equatorial stratosphere does play a part in determining the character of the circulation in the middle and high latitude troposphere, at least during mid winter and mid summer.

In view of the small sample of years used in calculating the mean charts it would be unwise to regard the results presented as ‘rules’. However, it might well be that when the data period, and our understanding of the general circulation, improves then the major stratospheric events, such as the QBO and the spring and autumn reversals of wind, will prove to be very useful parameters for forecasting on longer time scales.

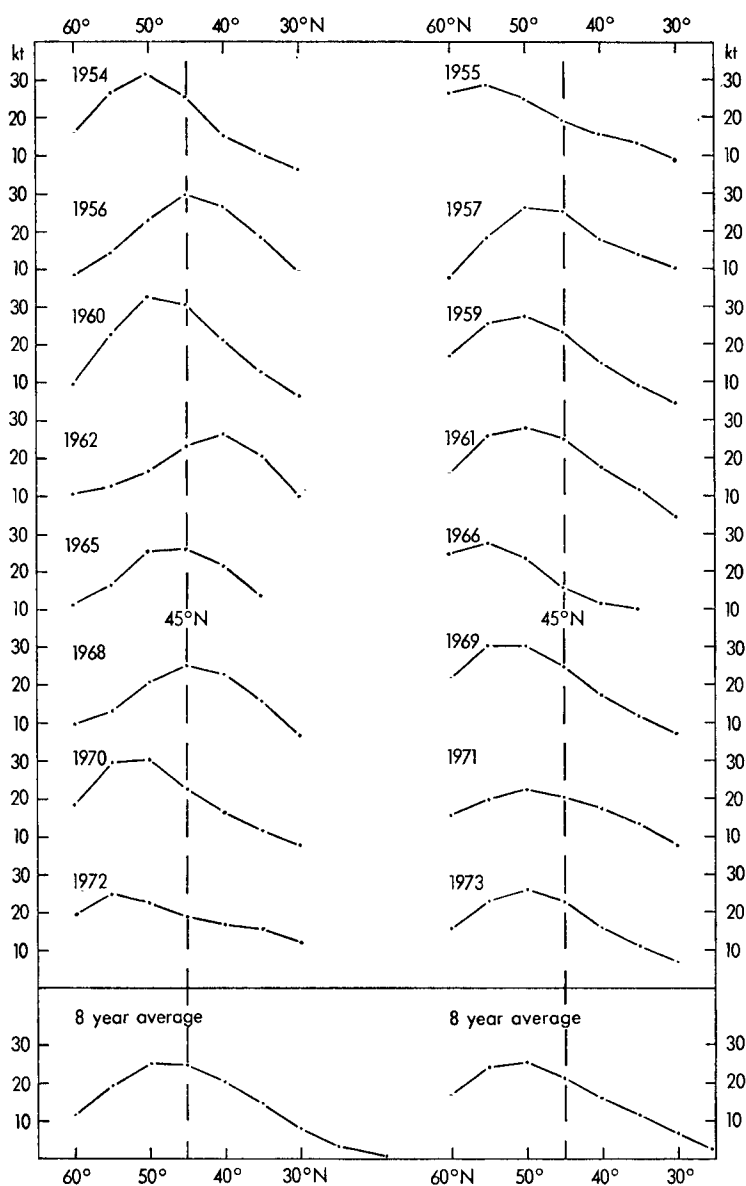


FIGURE 12—500-mb WIND SPEEDS MEANED ALONG LATITUDE CIRCLES OVER THE ATLANTIC FROM 60°W TO 0°, JULY

(a) Julys with easterly phase of QBO at 30 mb,
 (b) Julys with westerly phase of QBO at 30 mb.
 Wind speeds are in knots.



Photograph by C. J. Richards

PLATE I—TOWERING CUMULUS AND CUMULONIMBUS

The photograph, taken from Bristol Downs, looking north, on the evening of 24 July 1971, shows towering cumulus and cumulonimbus within a line of convergence over South Wales exhibiting pronounced convective activity within an unstable atmosphere.



PLATE II—NEW JOINT FINANCING AGREEMENT ON NORTH ATLANTIC OCEAN STATIONS

Mr N. Bradbury, Deputy Director (Observational Services) in the Meteorological Office, signing the Final Act of the Conference of Plenipotentiary Delegates on 15 November 1974. (At the time of writing the agreement still awaits ratification.)
See page 311.



PLATE III—NEW JOINT FINANCING AGREEMENT ON NORTH ATLANTIC OCEAN STATIONS

Sir David Hildyard, K.C.M.G., D.F.C., H.M. Ambassador and U.K. Permanent Representative at the U.K. Mission to the United Nations at Geneva, signing the agreement (subject to ratification) on 12 February 1975.

Seated next to Sir David Hildyard: Dr D. A. Davies, Secretary-General, WMO.

Standing, left to right: Mr Sen Gupta, Personal Assistant to the Secretary-General of WMO, Mr J. J. D. Ashdown of the U.K. Mission in Geneva, Dr G. K. Weiss of the Operations and Facilities Division of WMO, and Dr K. Langlo, Deputy Secretary-General of WMO.

See page 311.

To face page 297



Photograph by C. J. Richards

**PLATE IV—OPTICAL PHENOMENA AT SUNSET ON 17 DECEMBER 1973 AT BRACKNELL,
BERKS., OBSERVED THROUGH BANDS OF CIRRUS AND CIRROSTRATUS**

Acknowledgements. The author gratefully acknowledges the help given by Miss H. Tellam, who wrote the computer program to apply Welch's test, and Mr. S. Lawson whose computer program provided the 500-mb mean wind speeds.

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ON A METHOD FOR ANALYSING ATMOSPHERIC OSCILLATIONS

By R. DEL LLANO and J. M.ª NUÑEZ

(IBM Madrid Scientific Center and Barcelona University respectively)

Summary. The results of analysing pressure data by means of Fast Fourier Transform techniques for the detection of atmospheric tides and other periodical phenomena are presented.

Introduction. The results of analysing pressure data by means of Fast Fourier Transform (FFT) techniques are presented. With this method, frequencies of all atmospheric tides can be detected as well as frequencies of other periodical phenomena which the classic Chapman–Miller method¹ of studying atmospheric tides cannot discover.

Method of analysis. The aim is to calculate the power spectrum of a complete time series of three years' (1970–72) hourly pressure data (26 304 data in total). The measurements have been made from records registered by a microbarograph located in Barcelona (at 94 m above mean sea level, latitude $41^{\circ}23'07''$ N and longitude $2^{\circ}07'03''$ E). Each datum represents the average hourly pressure and not its instantaneous value, the mean being obtained graphically from the records by the equal-area method.* In this way the original time series is found to be convoluted with a regular time window of one hour width, and afterwards sampled at one-hour time intervals.

The calculus of the power spectrum is performed by means of the FFT algorithm proposed by Singleton² and is carried out in only one program-run with all the 26 304 data at the same time. Once the power spectrum is obtained it is multiplied by $(\pi f \tau)^2 / \sin^2(\pi f \tau)$, (where τ is the averaging time, 1 hour in this case) in order to counteract the effect of the time averaging. In the Figures the value of $p \times f$ is plotted against $\ln f$ (p being the value of the calculated power spectrum corresponding to the frequency f).

The complete spectrum. The results of the calculations previously described give us about 13 000 power estimates, covering a range of frequencies from 3.8×10^{-5} to 0.5 cycles/hour.

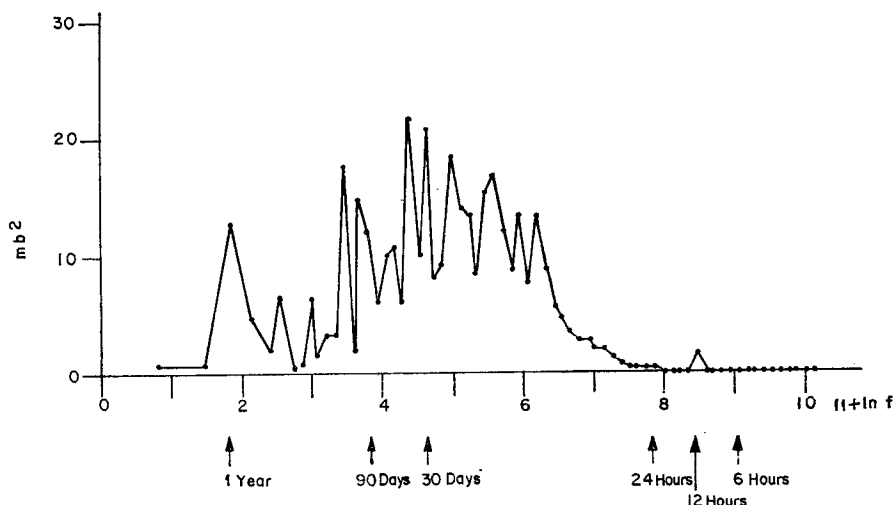


FIGURE 1—POWER SPECTRUM OF THREE YEARS' HOURLY PRESSURE DATA IN BARCELONA

* Such data are available on an 800-bpi magnetic tape in the 'Departamento de Física de la Tierra y del Cosmos', Avda. Generalísimo Franco, 647. Barcelona-14, Spain.

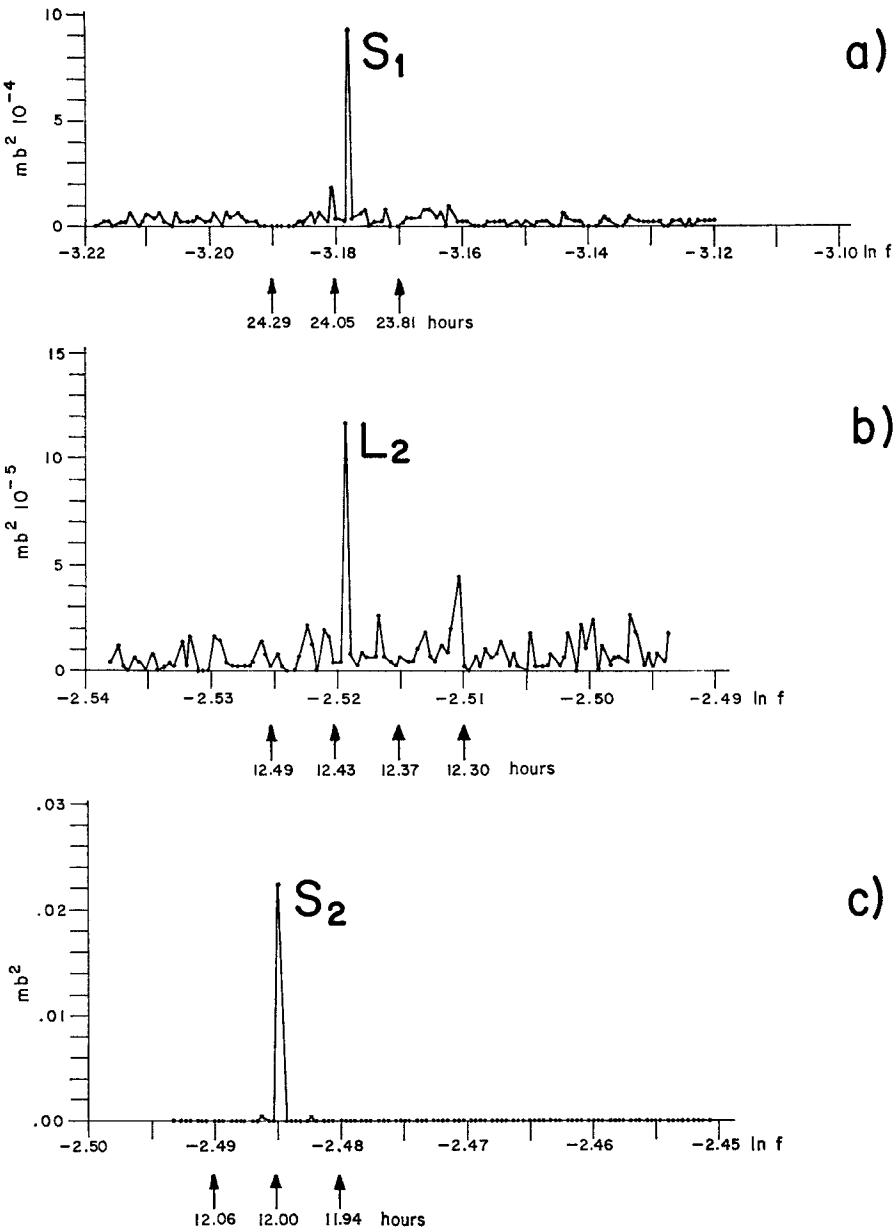


FIGURE 2—DETAILS OF PRESSURE POWER SPECTRUM: SPECTRAL BANDS SHOWING SOLAR AND LUNAR TIDES

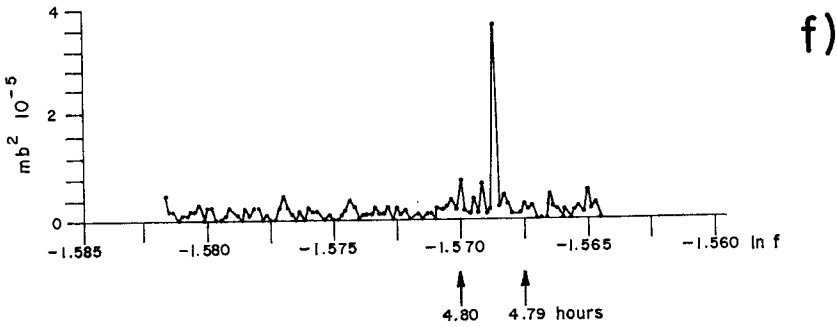
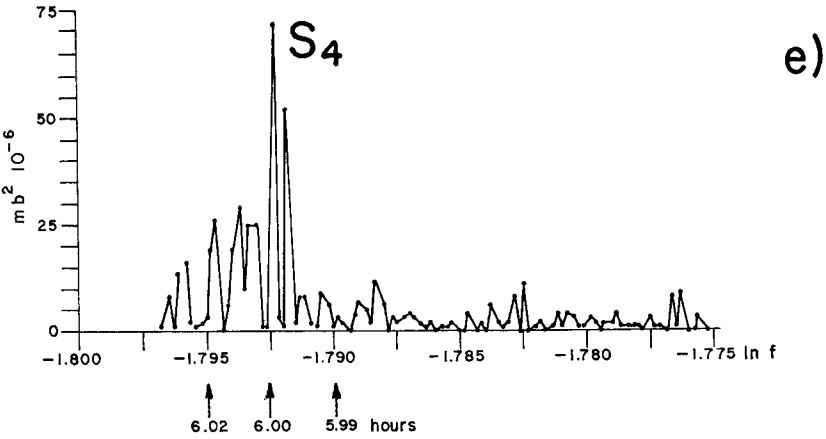
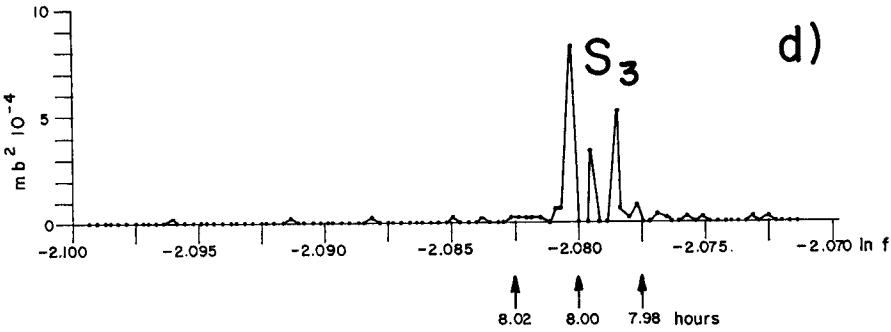


FIGURE 2—continued

In order to have a complete description of the spectrum and to solve the problem of plotting the 13 000 power estimates in the same Figure, the following procedure has been used: the frequency axis is divided into 69 uniform spectral bands in accordance with a logarithmic scale (in such a way that the higher the frequency, the greater the number of spectral estimates in each band). In Figure 1, the average $\overline{p \times f}$ in each of the 69 bands is plotted against the corresponding average $\ln f$. An extra scale has been added to the abscissae, where the periods in hours and days are shown to make the interpretation of the graphs easier.

There are two characteristics that can be clearly detected in this first Figure: on the one side, the yearly pressure oscillation, associated with a very clear peak that appears in the low-frequency part of the spectrum, and on the other side, pressure oscillations with periods greater than 24 hours whose amplitudes dominate clear oscillations with higher frequencies (this fact must be understood as the influence of the synoptic baric systems).

For periods smaller than 24 hours only one peak can be detected clearly, and it can be associated with the semidiurnal solar tide. The fact that other components of atmospheric tides are not present in this Figure can be understood if we take into account that the points in the graph are the average of several estimates and not the estimates themselves, so the narrow peaks associated with atmospheric tides are eliminated by the averaging procedure.

Conclusions. Figure 2 shows in detail all these spectral bands, of 100 estimates each, which show interesting aspects. From the clearness of the peaks which appear in some of the spectral zones and from their perfect concurrence with the fundamental periods, they can be made to correspond perfectly to the principal components of the atmospheric tides: Figure 2(a) with daily solar tide S_1 , Figure 2(b) with semidiurnal lunar tide L_2 , Figure 2(c) with semidiurnal solar tide S_2 , and Figure 2(d) with terdiurnal solar tide S_3 . On the other hand in Figure 2(e) a pressure fluctuation appears less clearly and also shows a slight discrepancy between the peak period and the theoretical six-hour period which would correspond to the quaterdiurnal solar tide S_4 . It is also interesting to point out another peak area in Figure 2(f) which corresponds to an approximate period of five hours. Keeping in mind the geographical variability which Kertz³ had already obtained for the S_4 component, these results bring us to consider the necessity of introducing other elements, possibly local ones, in the theory of thermal influence on atmospheric oscillations. In any case, this method appears to be highly promising for a complete study of atmospheric oscillations.

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ESTIMATION OF THE LIFE SPAN OF ATMOSPHERIC MOTION SYSTEMS BY MEANS OF ATMOSPHERIC ENERGETICS

By GY. KOPPÁNY

(Central Forecasting Institute of the National Meteorological Service, Budapest)

Summary. Comparisons have been made between the kinetic energy and the life span of various atmospheric motion systems. The mechanical power of the motion systems increases with the increase in size, but it is limited by the solar energy absorbed in the earth-atmosphere system on the one hand and by the net efficiency of the atmosphere on the other. An estimate is made of the period needed for the generation or transformation of the global atmospheric circulation.

When either statistical or dynamical methods are applied to the preparation of long-range weather forecasts it is most important to ask how long the forecasts can be extended with a relatively high probability of success; in other words, how long is current weather dependent on the previous stage of the earth-atmosphere system.

An attempt was made by Bonacina¹ to answer this question. He pointed out that according to some estimates, the weather depends on the past 15 days or for several times that period. Lorenz² applied a numerical model to the investigation of the predictability of the weather. In this numerical model he distinguished between 20 scales, each covering an octave of the spectrum, starting with the smallest air motion and going on to the largest atmospheric current, that is to say the global circulation of the atmosphere. He concluded that the predictability depends on the size of the motion, and that even the largest atmospheric currents cannot be predicted by means of a numerical model for longer than two or three weeks.

Baur³ used monthly mean values of atmospheric parameters in his thorough statistical analysis. He investigated the iterations of the monthly anomalies of atmospheric parameters and found that those in the first three months are smaller, but in the fifth and sixth months they are larger than those expected in theory. His conclusion is that the atmosphere has a tendency towards repetition rather than towards persistence—*Wiederholungsneigung* instead of *Erhaltungsneigung*.

It is well known that the life span of air motion increases with the size of the motion, for example the duration of a small whirlwind is no longer than one minute, a local thunderstorm is over within a couple of hours, the life span of a cyclone is 7–15 days, and so on. Since both horizontal and vertical dimensions of an air motion system can be estimated more or less accurately we are able to estimate the mass of moving air in a motion system. Thus, taking into account that most air motions have a wind speed of 10 metres per second, we may calculate the amount of kinetic energy in a motion system.

Let us pick out seven motion systems of various sizes, starting with the smallest and going to the largest, and compare their kinetic energy with their life duration. If the kinetic energy is given in joules (J) and the time in seconds (s), the following estimates can be made:

- | | | | |
|--|---------|-------------------------|----------|
| 1. Small whirlwind | .. .. . | 10^4 – 10^5 J | 10 s |
| 2. Local circulation cell without precipitation, | | | |
| e.g. single cumulus | .. .. . | 10^{10} – 10^{11} J | 10^2 s |

3. Local thunderstorm	.. .. .	10^{14} J	10^3 s
4. Cold front	.. .. .	10^{17} J	10^5 s
5. Extratropical cyclone	.. .. .	10^{18} – 10^{19} J	10^6 s
6. Frontal zone consisting of series of cyclones on surface accompanied by Rossby waves aloft		10^{20} J	10^7 s
7. General circulation of the atmosphere	.. ..	10^{21} J	?

The above values can be depicted in a co-ordinate system, in which the X-axis denotes kinetic energy and the Y-axis is the life span of the motion systems, these being represented by the letters A–G.

From Figure 1 it can be seen that the life span of motion systems increases slowly at smaller motions with increasing kinetic energy, but it increases rapidly at larger motions. However, the question remains what is the life span of the general circulation? Actually we know the order of magnitude of kinetic energy of the general circulation; thus we may draw a vertical line in Figure 1 at 10^{21} J indicating that this is the highest limit of kinetic energy forming in the atmosphere. The task is to determine the point where the curve in Figure 1 crosses the vertical line of 10^{21} J. The ordinate of this point will give the duration of the general circulation.

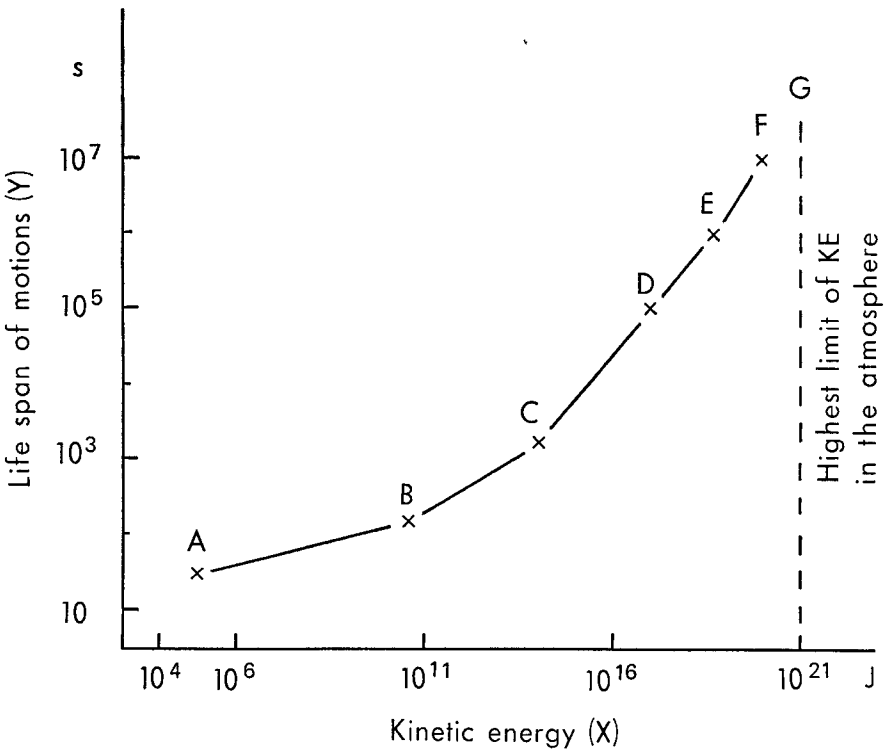


FIGURE 1—LIFE SPAN OF ATMOSPHERIC MOTION SYSTEMS AS A FUNCTION OF KINETIC ENERGY

The letters A–G represent systems of increasing size from small whirlwinds to the general circulation.

In order to answer this question let us calculate the ratio X/Y , that is to say (kinetic energy)/(life span of the motions). In fact the ratio X/Y has a well-defined physical meaning—generation, conversion or dissipation of kinetic energy; in general, the mechanical power of the motion system. In this case the conversion of kinetic energy will be given in joules/second or watts. We have next to estimate the area in m^2 touched by a given motion system and calculating the ratio W/m^2 we shall obtain the conversion of kinetic energy per square metre. This quantity is comparable with the solar energy absorbed by the earth-atmosphere system over $1 m^2$ horizontal area.

The order of magnitude of the solar energy is 10^{17} watts over the whole earth, or 10^3 watts per square metre. On the other hand, the ratio of conversion of kinetic energy to solar energy, that is to say the *net efficiency of the earth-atmosphere system*, has been determined by many authors. The value of this ratio is approximately equal to 10^{-3} ; thus about one-thousandth of the solar energy is being converted to kinetic energy in the earth's atmosphere (Borisenkov⁴). Thus we have two very important characteristics of the mechanism of the general circulation of the atmosphere, namely the solar energy as the source of energy generating all motion in the atmosphere, and the net efficiency of the earth-atmosphere system.

Having calculated the ratio X/Y in joules/second, we have obtained very important results, summed up in Table I. The ratios of X/Y , i.e. the *mechanical powers* of motion systems increase with the size of the motions. However, they have a highest limit value of 10^{14} J/s or 10^{14} W, which is determined by the solar energy and the net efficiency of the atmosphere. Dividing the kinetic energy by the mechanical power of the atmosphere we get 10^7 s for the life span of the general circulation. One possible interpretation of this result may be that the generation of the global circulation system of the earth's atmosphere by given solar radiation lasts 10^7 s, that is to say about four months or so.

TABLE I—KINETIC ENERGY, DURATION, AND MECHANICAL POWER OF ATMOSPHERIC MOTION SYSTEMS OF DIFFERENT SIZES

Motion system	Kinetic energy (X) joules	Life span (Y) seconds	Power (X/Y) watts	Area m^2	Power per unit area W/m^2
Small whirlwind (A)	10^4-10^5	10	10^3	10^2	10
Local convection cell without precipitation (B)	$10^{10}-10^{11}$	10^2-10^3	10^8	10^5	10^2
Local thunderstorm (C)	10^{14}	10^3-10^4	10^{10}	10^8	10^2
Cold front (D)	10^{17}	10^5	10^{12}	10^{11}	10
Extratropical cyclone (E)	$10^{18}-10^{19}$	10^6	10^{13}	10^{13}	1
Frontal zone (F)	10^{20}	10^7	10^{13}	10^{13}	1
General circulation (G)	10^{21}	10^7 (?)	10^{14}	10^{14}	1

This result may be compared with results obtained from other planets; for instance Venus has an atmosphere about 90 times larger in mass than that of the earth, and perhaps 100 or 1000 times the kinetic energy is possible in the atmosphere on Venus than on earth, but not more than twice the solar energy. If the net efficiency of the atmosphere on Venus is 10^{-2} or 10^{-1} , then the span of life of the global circulation on Venus may be estimated at 10^9 seconds, about 100 times longer than on the earth. Similar estimates could be made for Mars, and we get a value of 10^6 seconds for the life span of the general circulation on Mars.

Computations were made by Adem⁶ to examine the response of the Atmospheric–Oceanic–Continental system to an initial surface ocean temperature anomaly of 2 degC over the whole oceanic area. The results proved that such an anomaly could even affect the mean surface temperature of the earth as much as three or four months later.

Some other comparisons of the results are seen in Table I. At present the largest source of man-made energy, hydroelectric stations have achieved a mechanical power of about 10^9 watts, which is comparable to the power of a local thunderstorm, but the latter only works for a couple of hours. A bus has generally a mechanical power of 10^4 – 10^5 watts, which is the equivalent in mechanical power of a small whirlwind; the former is about 10 times larger. An airliner may have a mechanical power of 10^7 watts which is thus comparable with that of a local convection cell. It is evident that the total power of a local convection cell might keep an aircraft in the air for 10–20 minutes.

The last column of Table I contains the results obtained for the mechanical power of the motion systems per square metre. It is worthy of note that the net efficiency of the smaller motion systems may exceed that calculated as characteristic of the whole atmosphere, but that of motion systems like extra-tropical cyclones or larger motions does not exceed that value. It must be taken into consideration that cold fronts, local thunderstorms and smaller atmospheric motions have their energy conversion effects concentrated in a relatively small area.

Finally we have to consider that the earth–atmosphere system is much more complicated than any man-made engine. The energy conversions in the earth–atmosphere system can be outlined thus: radiation, sensible heat (and latent heat), potential energy, available potential energy, kinetic energy, sensible heat, radiation. A great number of factors contribute to this energy cycle, such as turbidity of the atmosphere, albedo both of the atmosphere and of the surface, cloudiness, humidity of the soil, ocean currents and so on. A drastic change in one of these factors will cause changes in other factors. This process has been called ‘feedback mechanism’ by Namias⁵ and has been extensively examined by him.

It is evident that the stronger the initial change (anomaly or disturbance) or the larger the area affected by this initial change, the longer the duration of the anomaly in the general circulation and weather. Hence the duration of transformation of large-scale motions in the atmosphere may be much longer, perhaps several times longer than we calculated by means of the mechanical power of the solar radiation and the net efficiency of the earth–atmosphere system.

It should be mentioned that the recent investigation of the long-range extrapolation of analogies has produced conclusions which apparently support the above calculation of the life span of large-scale motions (Koppány^{7,8}). It was found that the success of extrapolations of similar years based on hemispheric monthly mean temperature fields does not decrease at a steady rate with the length of the extrapolation, but takes the form of a slowly declining oscillation. The effectiveness of extrapolation of the monthly temperature data for Budapest decreases with the length of the extrapolation up to the seventh month, then regular maxima are found until the 21st month. This means that the initial stage of the atmosphere may affect the weather for nearly two years.

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REVIEWS

Air pollution and atmospheric diffusion, edited by M. E. Berlyand. 245 mm × 175 mm, pp. vi + 242, illus. (translated from Russian by Israel Program for Scientific Translations, Jerusalem), John Wiley & Sons Ltd, Baffins Lane, Chichester, Sussex, 1974. Price: £10.80.

This publication is a collection of 27 papers on various aspects of atmospheric pollution. Edited by M. E. Berlyand, it probably represents an overall view of recent trends in Soviet research on the subject. The original Russian version was published in 1973, and the process of translation has been reasonably quick, so that the contents are still reasonably up to date.

The papers cover a wide range of topics, and are not in any systematic order, but the subjects may be classified in four groups, namely:

- (a) methods of sampling and measurement of various types of pollutant,
- (b) observations of the distribution of pollutants,
- (c) forecasting atmospheric pollution, using meteorological observations or forecasts, and
- (d) pure meteorology.

The reviewer is not well qualified to judge the papers in the first group, but one commendable feature is the recognition of the need for comparison of the instruments used in different countries, and for the standardization of procedures. Much effort appears to be going into the development of new techniques and the improvement of existing ones.

Of the papers dealing with measurements of atmospheric pollution, most discuss also the interpretation of the observed distributions in terms of the nature and location of the sources and of the pertinent meteorological factors. These papers vary a good deal in their approach to the interpretation of the observations. Particularly interesting is the use by some authors of statistical tools such as spectral analysis and empirical orthogonal functions to separate

the effects of local and distant sources and to distinguish between variations arising from meteorological causes and those dependent upon source characteristics. A further use of the statistical studies is in the determination of the optimum network of sampling stations and the best sampling programme, depending upon the variability of the pollution concentration in time and space and upon the error of measurement, as well as on cost. At the other end of the scale, some papers merely quote the measurements or give a very simple qualitative explanation of the findings.

Two further topics may be included in this group. One paper deals with the design of an experiment to test theoretical models, developed by Berlyand, of the dispersion of pollutants from a stack in a wide range of meteorological conditions. The results appear to show reasonable agreement between theory and experiment. The second topic, the wash-out of aerosol by precipitation, is discussed in two papers. One paper suggests that the largest aerosol particles are washed out most efficiently, while the other concludes that there is a range of particles for which wash-out is least efficient, the lower limit (0.75 to 4 μm) depending upon the intensity of turbulence, while the upper limit (3 to 10 μm) is determined by the size of the precipitation particles.

The two papers on the forecasting of pollution approach the problem from a statistical viewpoint: one study uses a multiple discriminant analysis, but one cannot be confident that in this type of work such complexity is necessary or worth while.

The final group of papers deals with pure meteorology, the longest and most important being a contribution by Berlyand himself on a numerical model of radiation fog formation and development, with a short section on the effect of fog on the behaviour of pollutants. Other papers discuss urban effects on temperatures near the surface and in the boundary layer, the duration of light winds and inversion conditions at various locations, and, finally, the requirement for more detailed and accurate meteorological measurements in the boundary layer for improving our knowledge and understanding of the behaviour of pollution.

Overall, the publication shows that pollution problems are receiving a good deal of attention from Soviet scientists, and that much useful work is being done. Although at the price few individuals will wish to buy the book it is a worthwhile acquisition for the libraries of any establishment which carries out work related to pollution.

J. CRABTREE

Science and the weatherman, by Trevor Baker. 245 mm \times 175 mm, pp. viii + 63, illus., A. Wheaton and Company, Hennock Road, Exeter EX2 8RP, 1974. Price: 75p.

This is a light-weight addition to the range of popular books on 'the weather business', written by an ex-forecaster who now works for commercial television. It is published by a firm of educational publishers, but the book seems really to be directed beyond the schools to the whole range of the author's television audience, of all ages.

There are 11 short chapters including one on the author's daily drill as a television weatherman. Pictures take up one third of the available space and are good, but the diagrams are a disappointment. It is a pity that all the skills of modern television presentation cannot combine simplicity with realism in a more satisfactory manner. The text is written in a hearty, popular style and is as free of misleading statements as one can expect in a popular book. Though even at this level, to read 'We are all affected by the winds' makes one wonder if one is tuned in to the right programme.

In schools this would be a book for the library, not the classroom. It is a well-produced trifle and could stimulate the general interest of many.

P. G. WICKHAM

Atmospheric thermodynamics, by J. V. Iribarne and W. L. Godson. 245 mm × 170 mm, pp. x + 222, *illus.*, D. Reidel Publishing Company, P.O. Box 17, Dordrecht, Holland, 1973. Price: Dfl.65.

The authors point out that while many textbooks on dynamical meteorology contain one or more chapters on the thermodynamics of the atmosphere, there is no work in English devoted entirely to the subject. This book has been written to fill the gap and does indeed give a fuller and more satisfactory treatment.

The first three chapters, comprising about one-quarter of the text, give a brief review of the basic principles of general thermodynamics. The first and second laws of thermodynamics are discussed and related to topics which arise in the later chapters. Entropy is introduced by applying an integrating factor to the energy equation and the Carnot cycle is used to define a thermodynamic temperature scale. Although condensed, these chapters are sufficiently full to enable the interested science graduate to cope with the remainder of the text. In Chapter 4 'Water-Air Systems' the idea of a heterogeneous system is introduced and illustrated by considering water substance and its phase changes in the atmosphere. A section on the thermodynamics of moist air follows in which virtual temperature and various humidity parameters are defined.

The remaining two-thirds of this book are more completely meteorological in content. A chapter on aerological diagrams describes the most widely used diagrams and the sets of fundamental isopleths. This is followed by a chapter on thermodynamic processes in the atmosphere in which consideration of isobaric and wet and dry adiabatic processes leads to the definitions of dew and frost points and wet-bulb and equivalent temperatures. The problem of condensation trails receives a fuller treatment than is usual in more general meteorological texts. After a short chapter covering geopotential and lapse rates in a variety of special atmospheres, the final and longest chapter deals with vertical stability in some detail. Here the parcel method is fully developed and the effect of vertical motion on the stability of a layer discussed. There is also a detailed treatment of the factors leading to variation of stability of both dry and saturated air. The chapter closes with an introduction to internal and potential energy in the atmosphere and the treatment of Margules is used to illustrate the idea of available potential energy.

Each chapter is followed by a set of problems to which answers are given at the back of the book. These problems are well chosen to test the student's understanding of the preceding chapter and form a valuable adjunct to the text.

The authors have succeeded in producing a monograph adequate to the needs of students in meteorology and helpful to workers in allied disciplines. Unfortunately the price (over £12 at current exchange rates) is likely to keep it out of the hands of both sets of workers.

H. HEASTIE

Display and analysis of spatial data, edited by J. C. Davis and M. J. McCullagh. 220 mm × 150 mm, pp. xiv + 378, *illus.*, John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1975. Price: £12.

The editors of this book are John C. Davis of the Kansas Geological Survey, University of Kansas and Michael J. McCullagh, Department of Geography, University of Nottingham. It consists of papers written by participants at the NATO Advanced Study Institute Conference on Display and Analysis of Spatial Data, held in Nottingham in July 1973. There are three sections dealing respectively with the theoretical aspects of objective analysis, contouring algorithms, and the practical uses of objective analysis.

The title and the preface might lead readers to suppose that it is a book giving a comprehensive account of the state of the art in the very many sciences which have data-analysis problems. This is not so. In the theoretical section computer scientists and others will note the absence of material related to the development of the vector-space foundations of the subject. Scientists in those disciplines having analysis problems which are non-linear in the coefficient-space will find no account of the work of Fletcher, Powell, Davies, Swann, and Rosenbrock, to name but a few. Meteorologists, aware of the prodigious effort which has gone into objective analysis in their own field over the past two decades, may feel that the single sentence 'Meteorologists (Cressman 1959)

use as a weighting function $\lambda = \frac{R^2 - d^2}{R^2 + d^2}$, at the top of page 98, is somewhat

less than adequate reportage. The section on contouring is heavily biased towards American work in petrology, mineralogy, mining and related matters. There is no account of the large amount of work done on this topic at the National Physical Laboratory and at the Atomic Energy Research Establishment and the contribution of the Meteorological Office is covered, on page 153, by the quotation of half a sentence from a paper by Sawyer in the *Meteorological Magazine* for 1960. The last section deals with the use of objective analysis of stratigraphic data in pursuit of oil and mineral wealth, agricultural and sociological data in pursuit of better land-resource management, and topographical data to meet a variety of cartographical requirements. There is no

mention of the massive daily routine use of objective analysis of meteorological data at various world centres, nor is there any mention of the very large-scale problems in particle-trajectory analysis tackled at CERN (the European Organization for Nuclear Research), and the impressive achievements of the British aircraft industry, in collaboration with the Royal Aircraft Establishment and the National Physical Laboratory, in using multidimensional splines for the analysis of wind-tunnel data have apparently gone unnoticed.

None of the above strictures matter very much if the book is accepted for what it really is, namely an informative and valuable window on to the world of data analysis in the geological and geographical sciences, broadly interpreted. Geologists and meteorologists have worked on the same problem over the years but have been subjected to different pressures. For geologists the problem has been to make the best use of relatively small amounts of expensively acquired data. Their analyses have had to provide a basis for decisions the implementation of which might well involve further expense of an almost astronomical order. Not unnaturally, they have been much concerned with problems of assessment and interpretation. For meteorologists the problem is that they are confronted daily by a vast amount of data which has to be reduced to acceptable objective analysis by certain deadlines. It is a formidable real-time exercise, placing a premium on robustness and speed, with not a great deal left over for numerical introspection. With this different emphasis in mind, the book is required reading for all meteorologists having an interest in this area. The book is well set out, individual papers deal with their topics succinctly, and there are extensive references opening up a wide horizon for us. Of particular note for meteorologists are the papers dealing with 'Kriging', a form of objective analysis very closely related to Gandin's optimal interpolation.

R. DIXON

PUBLICATIONS RECEIVED

The following have been received from the Meteorological Institute of the University of Thessaloniki:

Meteorologika 41: *Soil temperature in Thessaloniki—Greece*. By G. C. Livadas and Yan. Ath. Goutsidou. 1974.

Meteorologika 42: *Weather types and atmospheric pressure in Thessaloniki—Greece*. By T. J. Makroyannis. 1974.

Meteorologika 43: *On the annual variation of air temperature in Larissa—Greece*. By A. A. Flocas. 1974.

NOTES AND NEWS

The new network of North Atlantic Ocean Stations comes into operation

The network of ocean meteorological stations in the North Atlantic, installed on special ships in fixed positions (NAOS network) came into operation on a new basis on 1 July 1975. Pending the entry into force of the new Agreement adopted by a Conference of Plenipotentiary Delegations in November 1974 for Joint Financing of these stations under the auspices of the World Meteorological Organization (see *Meteorological Magazine*, March 1975, pp. 90-91), the governments operating the ships decided to commence operation of the network in accordance with the terms of the Agreement. This decision was taken in view of the importance of such a network for forecasting and for providing meteorological services for various users in the North Atlantic, the Mediterranean and Europe and to a very large extent even the whole of the northern hemisphere.

The four ocean stations forming the network are located in the centre and east of the North Atlantic. Details of the network are as follows:

Station	Position	Operating country
C	52°45'N 35°30'W	Union of Soviet Socialist Republics
L	57°00'N 20°00'W	United Kingdom
R	47°00'N 17°00'W	France
M	66°00'N 02°00'E	Netherlands, Norway/Sweden

Each position will be permanently occupied by a ship specially equipped and staffed for carrying out a regular programme of meteorological observations: surface observations every hour, upper winds four times a day (at 00, 06, 12 and 18 GMT), upper-air pressure, temperature and humidity (radio-sondes) at least twice a day (00 and 12 GMT), preferably up to an altitude of 24 km or higher. These ships will also provide secondary services in connection with safety for the benefit of other ships or aircraft and making oceanographic observations. Continuous operation of each station necessitates two or three ocean-going ships.

Originally, in 1948, the NAOS network was set up under the auspices of the International Civil Aviation Organization mainly to provide adequate air-navigation facilities over the North Atlantic, including meteorological assistance. Since that time the importance of the network from an aeronautical point of view has decreased, whereas the network still plays an essential role for meteorological purposes. The continued operation of the network within the framework of an international agreement under the auspices of WMO is considered to be fully justified until such time as it is proved that the observations from these stations can be replaced by data obtained by other means such as satellites.

WMO PRESS RELEASE

Editor's note

The International Conference that decided on the establishment of the old network was held in London in September 1946. The first British weather ship to sail under these arrangements went on station in August 1947.

AWARD

Award of IMO Prize to Dr Warren Lehman Godson

We note with pleasure that the twentieth International Meteorological Organization Prize for outstanding work in meteorology and in international collaboration has been awarded this year to Dr Warren Lehman Godson, Associate Director-General, Atmospheric Research Directorate of the Atmospheric Environment Service, Department of the Environment, Canada, by the Executive Committee of the World Meteorological Organization.

THE INTERNATIONAL METEOROLOGICAL ORGANIZATION PRIZE

The International Meteorological Organization Prize was established in 1955 by the World Meteorological Organization in honour of the former non-governmental organization which initiated international collaboration in meteorology in 1873 and which was replaced in 1951 by the World Meteorological Organization when the latter was created as a United Nations Specialized Agency.

The award is marked by a gold medal, 1200 dollars (U.S.) and a diploma giving the citation of the award. The full list of recipients of the award since its inception is given below.

- Dr T. Hesselberg (Norway)—1956
- Professor C.-G. Rossby (Sweden and U.S.A.)—1957
- Mr E. Gold (United Kingdom)—1958
- Professor J. Bjerknes (Norway and U.S.A.)—1959
- Professor J. Van Mieghem (Belgium)—1960
- Professor K. R. Ramanathan (India)—1961
- Dr A. Ångström (Sweden)—1962
- Dr R. C. Sutcliffe (United Kingdom)—1963
- Dr F. Reichelderfer (U.S.A.)—1964
- Professor S. Petterssen (Norway and U.S.A.)—1965
- Professor T. Bergeron (Sweden)—1966
- Professor C. J. Kondratiev (U.S.S.R.)—1967
- Sir Graham Sutton (United Kingdom)—1968
- Professor E. H. Palmén (Finland)—1969
- Dr R. T. A. Scherhag (Federal Republic of Germany)—1970
- Professor J. G. Charney (U.S.A.)—1971
- Academician V. A. Bugaev (U.S.S.R.)—1972
- Dr C. H. B. Priestley (Australia) and Mr J. S. Sawyer (United Kingdom)—1973
- Professor J. Smagorinsky (U.S.A.)—1974
- Dr W. L. Godson (Canada)—1975

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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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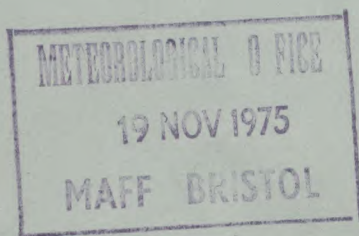
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CHANGES IN THE AREA OF ARCTIC SEA ICE 1966 TO 1974

By R. M. SANDERSON

Summary. This article presents the results of an investigation into recent changes in area of the northern hemisphere sea ice. It is shown that in both the winter and summer months the mean area for the period 1972-74 is slightly less than that for the period 1969-71. It is suggested that this decrease is also applicable to the two consecutive 4-year periods between 1967 and 1974.

Introduction. For some considerable time there has been a demand (from meteorologists, climatologists and others) for information on the year-to-year variability of sea ice in the northern hemisphere. Previously it has not been possible to meet this demand because ice limits around the whole region have not been sufficiently well defined to permit year-to-year comparisons to be made. The introduction of polar-orbiting meteorological satellites early in 1966, however, has allowed ice limits to be defined much more accurately, so that such comparisons can now be made. This investigation into variations in the areal cover of the Arctic sea ice since early 1966 was therefore undertaken.*

Data. To determine the area under sea ice the limit of 7/10 concentration was deliberately chosen since high concentrations of sea ice are of greater importance to meteorologists and climatologists in considering albedo and surface temperatures than are more broken ice conditions. Sea-ice limits of 7/10 were obtained from end-of-the-month sea-ice charts since early 1966. The charts used were those published by the Meteorological Office,¹ which are on a scale of approximately 1:21½ million and cover the area shown in Figure 1. They are based primarily upon data for the last 10 days of the month which means that only about one-third of the daily data are used in their construction. However, since ice-edge movements are generally very slow, it is considered that these charts are sufficiently representative of the total data to reveal any significant year-to-year changes in the area of sea ice.

The investigation was limited to the months of February, March and April, when the ice reaches its greatest extent, and to August and September when it

* Since this paper was received, the following account of further relevant investigations has been published: DICKSON, R. R., LAMB, H. H., MALMBERG, S.-A. and COLEBROOK, J. M.; Climatic reversal in northern North Atlantic. *Nature, London*, 256, 1975, pp. 479-482 (the issue of 7 August).

reaches its least extent. In the remaining months the ice edge is either advancing or retreating, according to the season, at varying rates which would tend to obscure any long-term trend in areal extent.

Over the Bering and Okhotsk Seas the data are available only from April 1968.

Method. The area under at least 7/10 cover of sea ice throughout the period of the survey (1966–74 in the ‘Atlantic’ sector and 1969–74 in the ‘Pacific’ sector) was determined for each of the five months investigated. It was found in each case by drawing the inner envelope of the lines of 7/10 cover in individual years given on the end-of-the-month charts. The area of ‘permanent’ ice cover each month was then calculated by counting the number of 1° ‘rectangles’ in each 1° latitude band, multiplying this figure by an appropriate factor to convert to areas in 10⁶ km², and summing for all latitude bands.

The variability of sea ice from year to year may be determined quantitatively by calculating the areas between the edge of the ‘permanent’ ice, and the line for 7/10 cover in individual years. This was done for each year of the survey using 1° rectangles in the manner described above. (For the purpose of this investigation, open water areas enclosed within areas at least 7/10 covered by ice were disregarded; they are too small to have any significant effect on the results.)

The edges of ‘permanent’ 7/10 ice cover, or the 7/10 minimum limits, for February and August are shown in Figure 1. The actual 7/10 ice edge for February 1972 is also displayed in order to give some indication of the area outside the 7/10 minimum limit for that particular year.

In order to permit a study of the relationship between ice conditions in one part of the hemisphere with those elsewhere, the areas under ice were tabulated by sectors. For the winter months the sectors were chosen to coincide with the various ice regimes around the Arctic, i.e. East Canada, Greenland Sea (east coast of Greenland and eastwards to 15°E), Barents Sea (including White Sea and Baltic), Bering Sea and Okhotsk Sea (see Figure 1). In the summer months, when the greater part of the ice edge lies within the Arctic Ocean, the ice cannot be divided into regions in this way. In August and September the sectors (0° to 90°E, 90°E to 160°E, 160°E to 130°W, 130°W to 85°W, 85°W to 0°) were chosen simply to facilitate the calculation of areas.

The area covered by the published monthly chart does not include the whole of the Pacific region affected by ice. The ‘off-chart’ parts of the Bering and Okhotsk Seas are shown in Figure 1. For these missing areas the 7/10 minimum and overall mean limits were drawn (from earlier post-war data) and the area between them was added where appropriate to each monthly area. The minimum, mean and maximum limits (the maximum being included to show the total variability) are shown for these areas in Figure 1. The error in using the ‘mean’ area for each month will be almost negligible since these ‘off-chart’ areas are relatively very small and the variability, especially in the eastern Bering Sea, is also small.

Results. The 1969–74 mean total areas under ice over the whole Arctic region are shown by months in Table I, which also gives the 1969–71 and 1972–74 means and the percentage decrease in mean area from the former to the latter 3-year period. The highest and lowest values and their departures from the 1969–74 mean, expressed as percentages, are also given. The mean values for

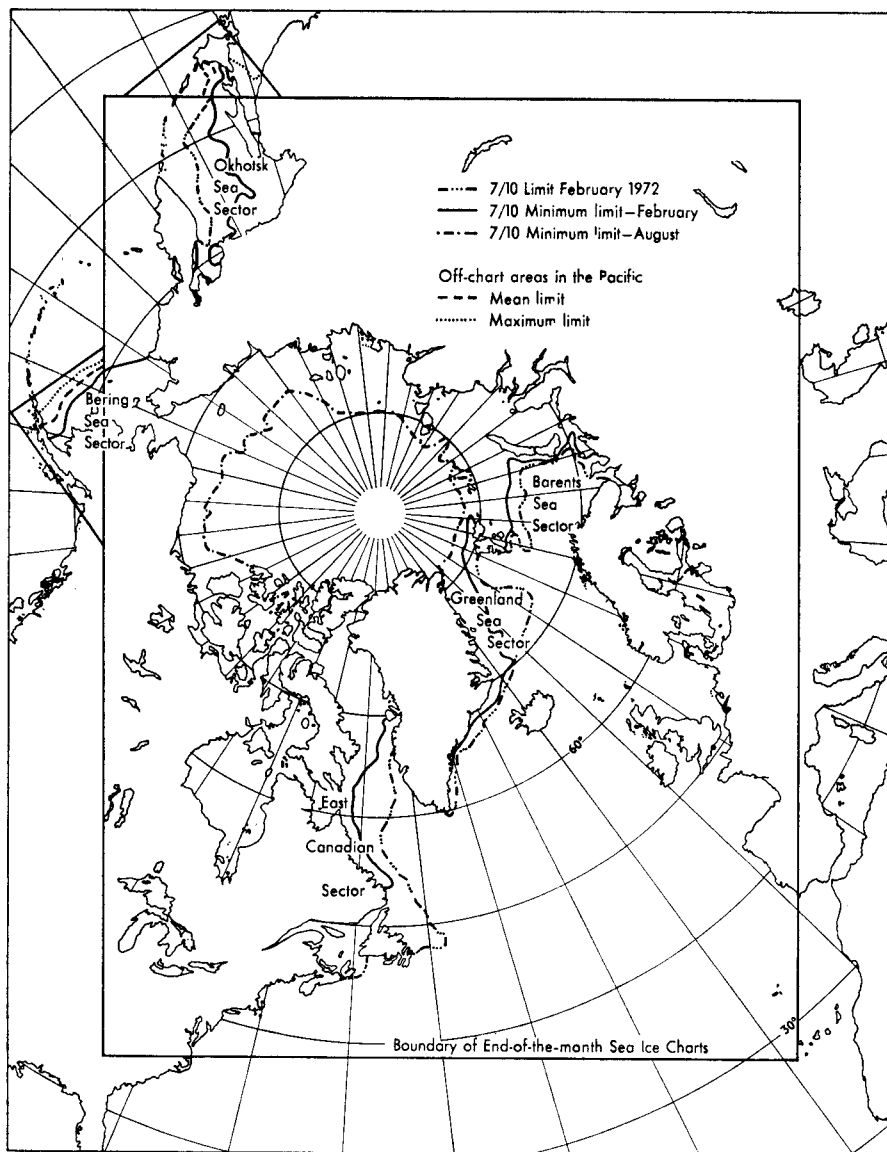


FIGURE 1—MAP SHOWING LIMITS OF 7/10 SEA ICE PER 1° 'RECTANGLE'

Note. The February 1972 limit coincides with the minimum limit in the western Bering Sea.

those parts of the total areas which are outside the 'permanent' ice edge or 7/10 minimum limits are similarly displayed in Table II.

Figures 2 to 6 show the results of the calculations of the sea ice areas outside the 7/10 minimum limit for each month. Each graph shows the variations from year to year in the area of sea ice for each sector and for the whole hemisphere. Areas for the 'Pacific' sectors and therefore also for the hemisphere are limited

to the 6-year period 1969-74 for reasons already discussed; but areas for the winter months in the 'Atlantic' sectors are shown in Figures 2, 3 and 4 for the whole period 1966-74.

TABLE I—MEAN TOTAL AREAS WITH 7/10 (OR MORE) SEA ICE ($\times 10^6 \text{ km}^2$)

	February	March	April	August	September
Mean 1969-74	15.47	15.19	14.01	6.58	6.88
Mean 1969-71	15.69	15.21	14.23	6.85	7.00
Mean 1972-74	15.25	15.17	13.80	6.32	6.77
1972-74 mean as a percentage difference from 1969-71 mean	-3	-0.3	-3	-8	-3
Maximum value	15.87	15.59	14.68	7.44	7.42
Year	1970	1969	1969	1969	1969
Minimum value	14.52	14.53	13.48	5.74	6.23
Year	1974	1974	1974	1973	1971
Departure from 1969-74 mean (per cent)	+3 to -6	+3 to -4	+5 to -4	+13 to -13	+8 to -9

TABLE II—MEAN AREAS OUTSIDE 7/10 MINIMUM LIMITS ($\times 10^6 \text{ km}^2$)

	February	March	April	August	September
Mean 1969-74	2.17	1.97	1.78	2.18	1.73
Mean 1969-71	2.40	1.99	2.00	2.45	1.84
Mean 1972-74	1.95	1.95	1.57	1.92	1.63
1972-74 mean as a percentage difference from 1969-71 mean	-19	-2	-22	-22	-11
Maximum value	2.57	2.37	2.45	3.04	2.28
Year	1970	1969	1969	1969	1969
Minimum value	1.22	1.31	1.25	1.35	1.09
Year	1974	1974	1974	1973	1971
Departure from 1969-74 mean (per cent)	+18 to -44	+20 to -33	+38 to -30	+39 to -38	+31 to -37

Discussion. It can be seen from Table I that, in every month, the 1972-74 mean was less than the mean for the previous three years. In February, April and September the decrease over the whole Arctic region was 3 per cent; in March it was 0.3 per cent and in August it was 8 per cent. The departures from the 1969-74 means of the maximum and minimum monthly values, also shown, can be quite large varying from +5 to -6 per cent in winter and from +13 to -13 per cent in summer.

The monthly graphs, Figures 2-6, indicate the contributions from each sector towards the 'total' areas outside the 7/10 minimum limit. It can be seen that heavy or light ice years over this 'total' area were not due to large or small ice areas, respectively, in each region. On the contrary, the graphs indicate that heavy ice conditions in one region are often largely off-set by simultaneously light conditions elsewhere.

Of particular interest is the relationship, in winter, between ice conditions in the East Canadian sector and those in the Greenland and Barents Seas. In February, March, and to a lesser extent in April, there is an inverse relationship between these regions in that heavy ice conditions occur simultaneously over the Greenland and Barents Seas while light conditions prevail off eastern Canada, and vice versa.

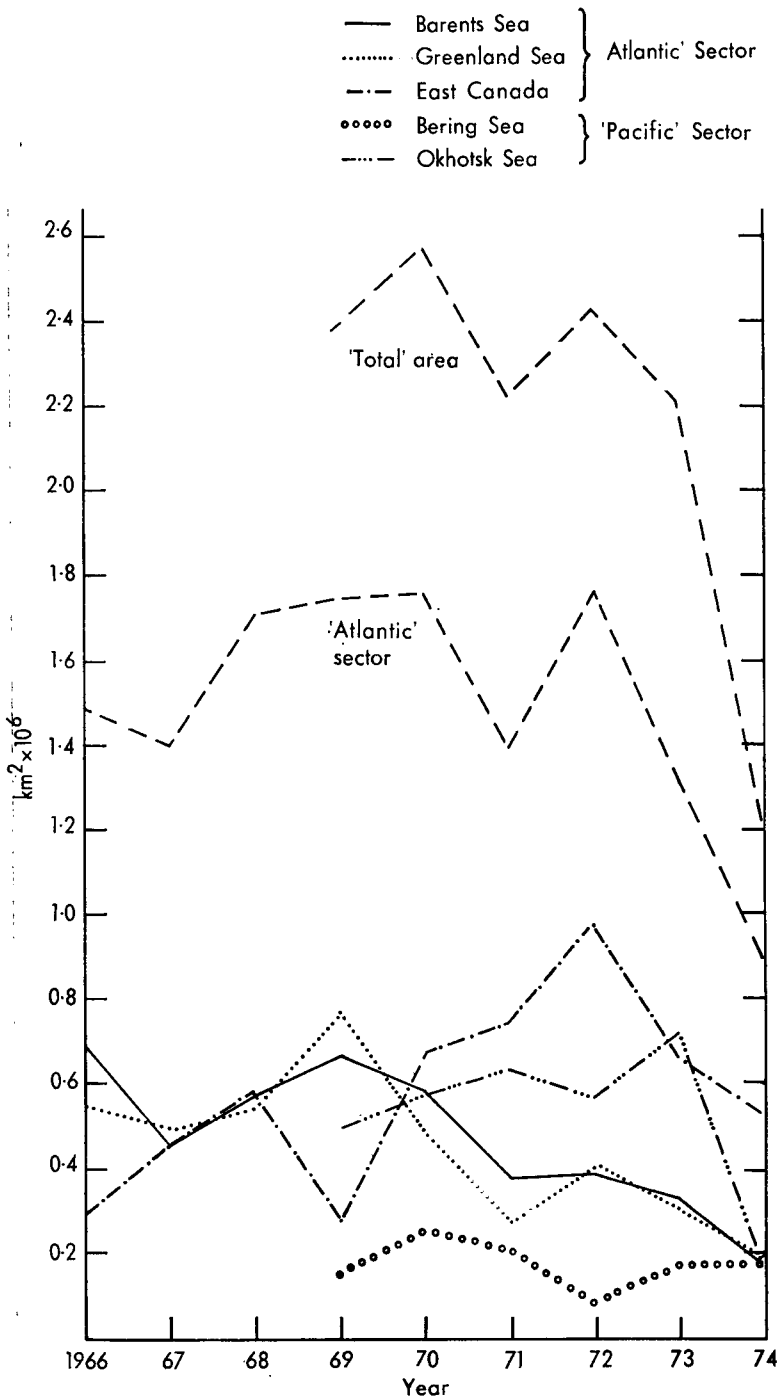


FIGURE 2—YEAR-TO-YEAR VARIATION OF AREAS OF SEA-ICE COVER IN FEBRUARY, OUTSIDE MINIMUM LIMIT OF COVER FOR WHOLE PERIOD
'Cover' implies at least 7/10 cover of sea ice per 1° 'rectangle'.

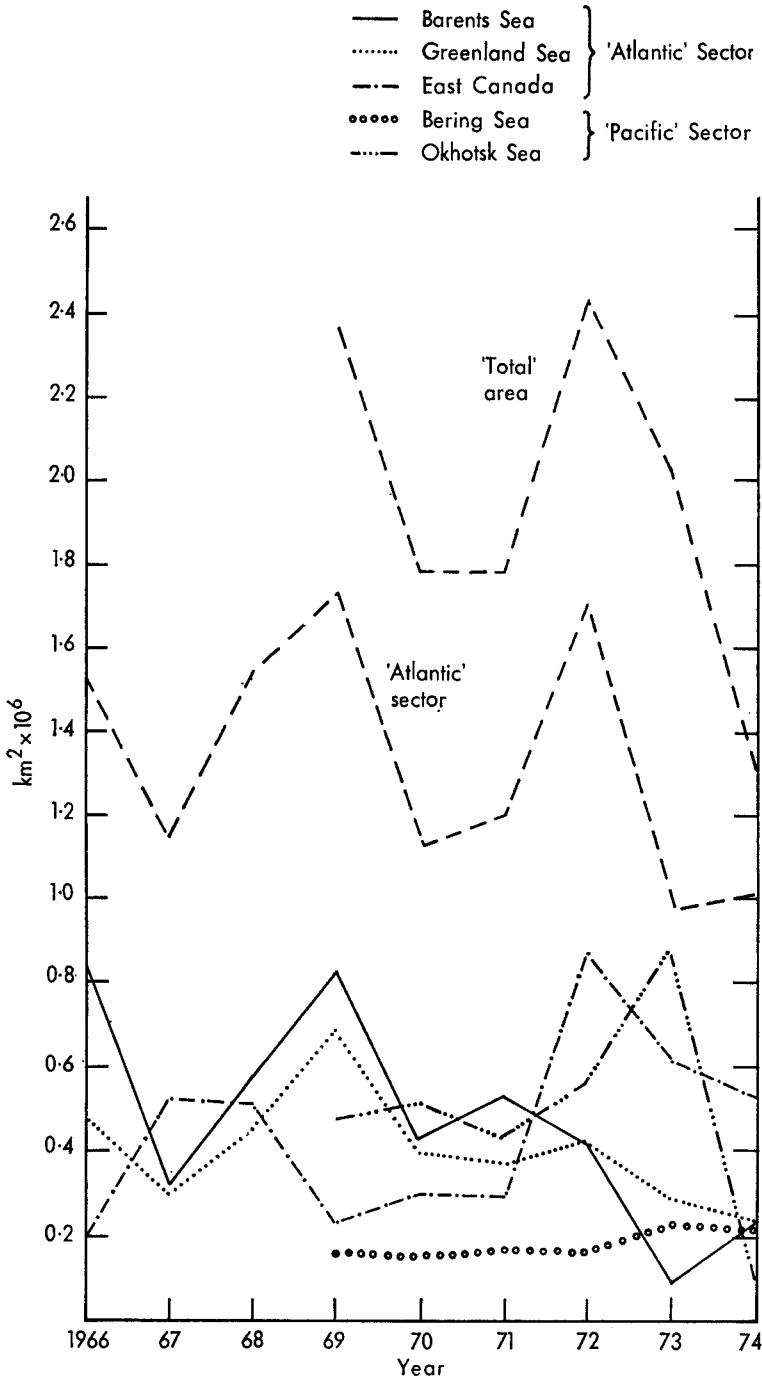


FIGURE 3—YEAR-TO-YEAR VARIATION OF AREAS OF SEA-ICE COVER IN MARCH, OUTSIDE MINIMUM LIMIT OF COVER FOR WHOLE PERIOD
See note under Figure 2.

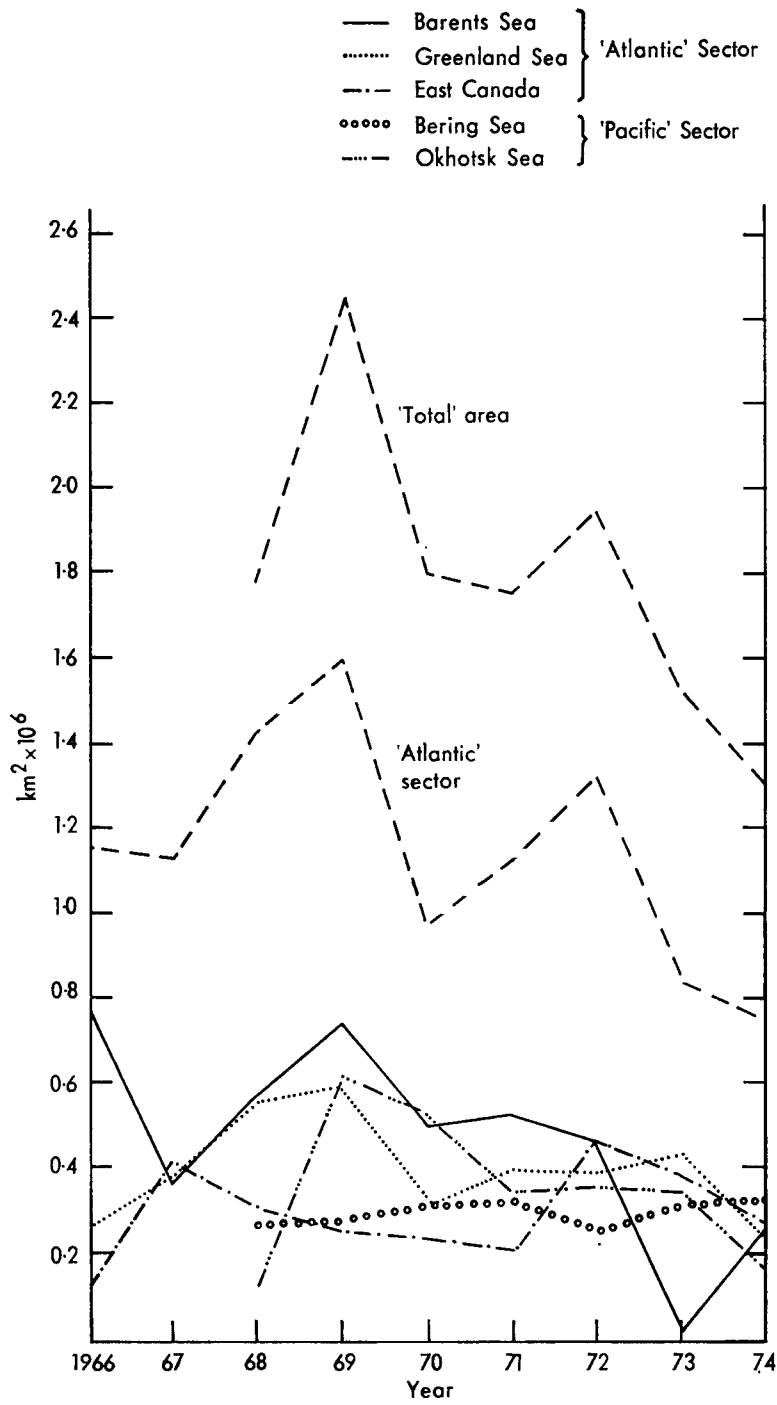


FIGURE 4—YEAR-TO-YEAR VARIATION OF AREAS OF SEA-ICE COVER IN APRIL, OUT-SIDE MINIMUM LIMIT OF COVER FOR WHOLE PERIOD
See note under Figure 2.

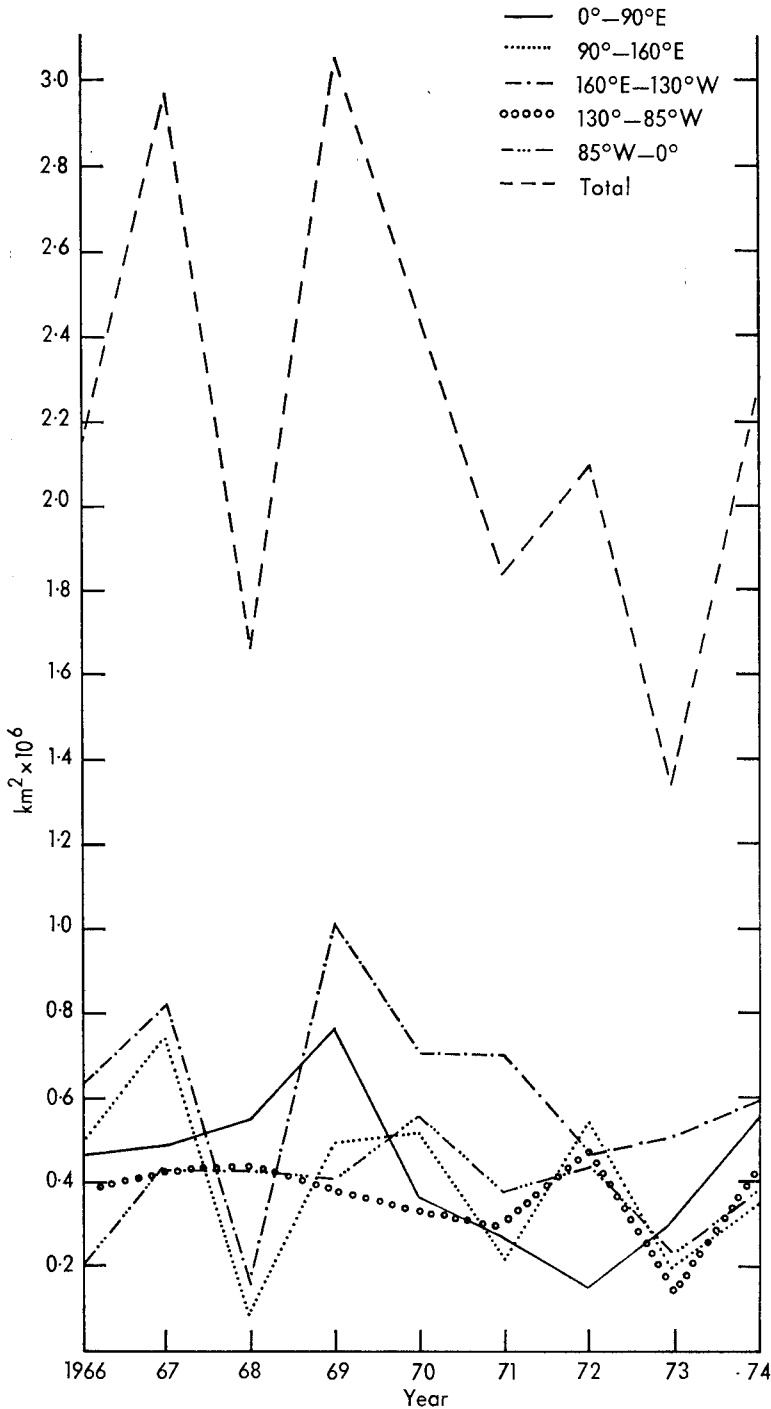


FIGURE 5—YEAR-TO-YEAR VARIATION OF AREAS OF SEA-ICE COVER IN AUGUST, OUTSIDE MINIMUM LIMIT OF COVER FOR WHOLE PERIOD
See note under Figure 2.

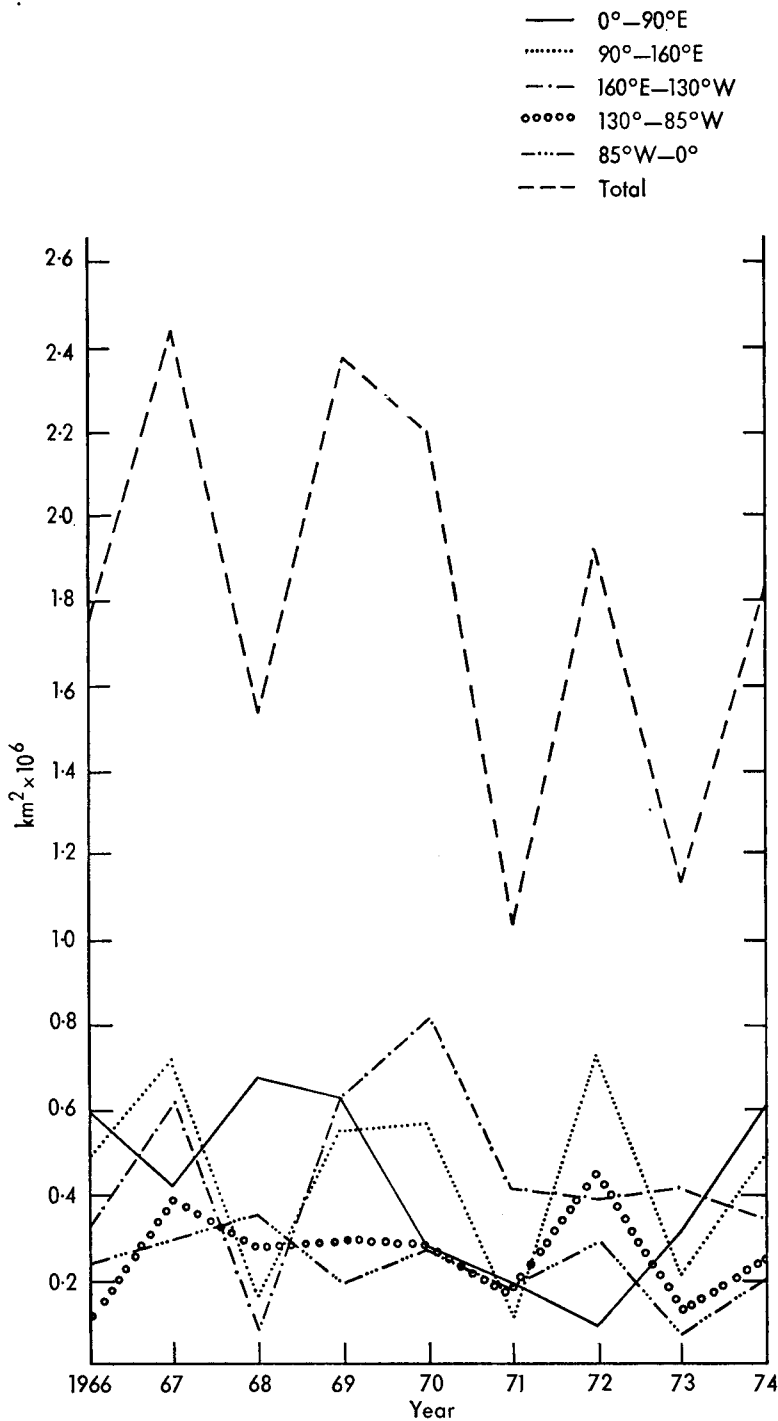


FIGURE 6—YEAR-TO-YEAR VARIATION OF AREAS OF SEA-ICE COVER IN SEPTEMBER, OUTSIDE MINIMUM LIMIT OF COVER FOR WHOLE PERIOD
See note under Figure 2.

There would also appear to be a fairly close direct relationship in February and March between conditions in the East Canadian and Okhotsk Sea sectors, though, at least during the period under investigation, maximum values in the Okhotsk Sea occurred one year later than off eastern Canada.

No consistent relationship between sectors is apparent in the summer months.

Anomalous sea-ice conditions are chiefly due to anomalous winds over the previous week or weeks.² In practically every region, heavy ice conditions are associated with winds from a north or north-westerly direction. A high degree of meridional flow at low levels is required to produce persistent winds from these directions in one or more regions. This would invariably lead to winds from some southerly direction in other regions which would in turn result there in unusually light ice conditions. For example, in February 1972 the large area of ice off eastern Canada resulted from a north-westerly wind anomaly over that region. In the same period a south-easterly anomaly prevailed off east Greenland resulting in light ice conditions in that sector.

The apparent direct relationship in February and March between conditions off eastern Canada and in the Okhotsk Sea may reflect the atmospheric long-wave pattern during the period 1969 to 1974 in these months. It is hoped to give a more detailed account of these relationships in a later article.

From the graphs for the winter months it can be seen that the general shape of the 'total' area curve is similar to the Atlantic sector curve for the common period 1969-74. This is because the Atlantic sector contributes twice as much as the Pacific sector towards the area beyond the 7/10 minimum limit in each of these months. It may reasonably be expected therefore that the percentage decreases in area for the period 1971-74 below those for the period 1967-70 for the total area will have been similar to those for the Atlantic sector. On this assumption the percentage decreases in total area from 1967-70 to 1971-74 would have been as follows: February 3 per cent, March 0.4 per cent and April 3 per cent. The corresponding decreases for the summer months are readily available from the data and were: August 9 per cent and September 9 per cent.

These figures clearly indicate that the percentage decreases from 1967-70 to 1971-74 are greater in the summer than in the winter months.

From Table I it can be seen that the mean area under 7/10 ice during the period 1969-74 is 15.47×10^6 km² in February (the month of greatest area) and 6.58×10^6 km² in August (the month of least area). Thus the mean annual range in the area of the northern hemisphere with 7/10 or more sea ice concentration is 57 per cent of the mean February amount.

Conclusion. Very large seasonal changes in the area of sea ice occur each year, and the changes in a given month from year to year are also sometimes considerable. But it is clear that the area under 7/10 ice cover, when meaned separately over two consecutive 3-year periods, has decreased slightly during the six-year period of complete hemispherical data coverage from 1969-74. It is suggested that this trend is also applicable to the two consecutive 4-year periods between 1967 and 1974. Extremely large changes in area may occur in some sectors around the hemisphere, but these are normally balanced by quite large changes in the opposite sense in other areas. The variability in the total area is usually less than 10 per cent.

Acknowledgement. I am indebted to Mr A. M. F. Blackford for his painstaking efforts in calculating the areas under ice.

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551.509.313:551.5095.

HUMAN INTERVENTION IN THE OPERATIONAL OBJECTIVE ANALYSIS

By F. SINGLETON

Summary. The recent enlargement of the intervention team in the Central Forecasting Office is indicative of the importance attached to the concept of subjective control over the objective analysis process. The problems presented by the various forms of data are described with a brief summary of the objective analysis sequence. The techniques of intervention, future developments and explanation of what appears to be a contradiction in terms are discussed by a member of the team.

Introduction. In the *Concise Oxford Dictionary* the verb 'to intervene' is defined variously as 'come in as something extraneous, occur in the meantime; come between, interfere, so as to prevent or modify a result etc.' In the Central Forecasting Office (CFO) the word is used to describe subjective modifications to the data used by the objective analysis programs as part of the numerical-forecast program suite.

The need for intervention is occasioned primarily by the problems of developing objective analysis techniques to cope satisfactorily with the large areas of sparse data that exist over the Atlantic and Pacific Oceans. For the purposes of numerical forecasting the CFO analysis area covers most of the northern hemisphere. Errors in numerical forecasting are often attributable in part at least to deficiencies in the analyses. The aim of the intervention team in CFO is to improve analyses to such a state that forecast errors might be assumed to be due solely to the formulation of the forecast programs or limitations in the basic concept of numerical forecasting. The consistent production of good analyses is an essential first step not only to good forecasting but also to the eventual elimination of defects in the forecast programs.

This note describes the use by CFO of subjective techniques to aid the production of good objective analyses. The theory and practice of the subjective modification and interpretation of the output from numerical-forecast programs have been discussed in a recent paper by Kirk.* These two papers, together, describe the complementary roles of human being and computer in the production of forecast charts.

* KIRK, T. H.; The use of numerical forecasts. *Met Mag, London*, 103, 1974, pp. 14-20.

The data

Conventional synoptic data. Over North America and Eurasia the quantity of data available is such that the objective analysis program can produce an optimum fit with greater consistency than can a human being. Over these areas the objective analysis is occasionally better and rarely worse than that made by an experienced human analyst. The computer is better at making systematic corrections to random instrumental error as well as allowing for systematic differences between various types of radiosonde equipment and varying practices in applying solar-radiation corrections.

Problems of analysis are somewhat greater over less well-populated land masses, those of North Africa and Arabia for instance, where the sparsity of data is such that random errors are more difficult to eliminate. However, small details in such areas are not generally essential to the production of numerical forecasts in higher latitudes. It is usually sufficient to maintain only a general level of pressure-contour heights.

Oceanic areas present the principal problems to both human and objective systems in that precise analysis in these areas is frequently of critical importance to the numerical forecast. Surface reports have marked diurnal variations in quantity because many ships carry only one radio operator. The distribution of data is also subject to annual variation due to the seasonal variability of routes taken by shipping. Difficulties in radio reception and inevitable errors both in transmission and reception of morse numerals cause the general quality of ship observations to be lower than that from land stations. Since the withdrawal of United States weather ships there have been large areas of ocean with no conventional upper-air data. Even areas where ship and island radiosonde data are received present similar problems to those from the sparsely occupied land areas—namely the detection of random instrumental errors and transmission errors.

Aircraft reports. These have long been used by forecasters as a valuable source of data supplementing conventional observations. Like ship reports there are, however, marked diurnal variations in the quantity of data owing to restrictions imposed by governments upon times of take-off and landing. The majority of aircraft winds are, in fact, not applicable to the main synoptic analysis times of 0000 and 1200 GMT. Although most aircraft reports are of high quality there are some occasions when the reported wind received at Bracknell is not consistent with that which might be expected at the reporting position. This is particularly evident when the aircraft has passed through a marked trough or ridge but there are other occasions when such errors are less easily detectable. Other errors can occur through distorted radio-telephony reception. Instantaneous winds measured by modern navigational equipment, although accurate, may, nevertheless, be unrepresentative of the large-scale flow. The main problem posed by aircraft winds, however, is that the winds whilst implying gradients of pressure-contour height do not give contour heights with which to associate the gradient. Some years ago aircraft reports used to contain a D-factor, the difference between pressure altitude and true height, from which a pressure-contour height could be deduced. The installation of radar altimeters in contemporary aircraft and the re-introduction of the D-factor would make a valuable addition to aircraft reports.

Satellite wind reports. These wind measurements are obtained by tracking cloud movements on pictures transmitted from the geostationary satellites

(GOES) situated over the equator. Experience in CFO has shown these to be very high-quality data and, being measurements over 20 minutes or so, very representative. Like aircraft winds, however, they only give gradients of contour height. Over the Atlantic these winds are available in areas where there is some cloud over an arc from about 45° north of the sub-satellite point (over the coast of Brazil) to the coast of West Africa. The main use of the satellite winds is the delineation of flow patterns at upper levels in areas where there are few aircraft.

SIRS. Satellite infra-red temperature soundings have, so far, proved to be among the least satisfactory of all the information used by the analyst. Heights of pressure levels deduced from these soundings are subject to large random errors in high latitudes while in low latitudes they were for several months generally too high, from 10 to 20 dam at 100 mb. Satellite temperature soundings are, probably, the most potentially valuable of all satellite data to the numerical forecast and this makes their lack of reliability to date all the more disappointing.

Satellite cloud pictures. These data are of great value to the human analyst as an aid to positioning surface frontal features, upper troughs, ridges, vortices and, sometimes, jet streams. By comparing visual and infra-red pictures the analyst can deduce the vertical and horizontal extent of cloud as an aid to the analysis of humidity fields.

The operational objective analysis. The first stage in the analysis sequence is the production of a background field or first-guess analysis. This is, in effect, a 12-hour forecast based on data from the last main synoptic hour over most of the octagon area but on persistence near the boundary. In areas where data are dense the analysis is determined almost exclusively by the new data; where data are non-existent the background becomes the analysis and in areas of sparse data the analysis is a mixture of background and data. This is analogous to the techniques of manual analysis where the analyst uses history from his last two or three charts and in areas of little data draws what is in effect a short-period forecast.

As data are received at Bracknell they are subjected to various quality-control programs. The communications computer lists for correction all messages with invalid indicators, addresses etc. The synoptic data bank (SDB) program tests for pressure-tendency consistencies, ship movements, correct date and time, hydrostatic consistency, temperature-dew-point consistency etc. Following these checks messages will be rejected in whole or in part or, in some cases, corrected. The accepted data form the Basic Analysis Data Sets (BADs) with rejected data remaining in the SDB as flagged data. During the operational analysis sequence CFO receives a full list of all data in the BADs as well as a list of flagged data with reasons for flagging.

The objective analysis fits a polynomial of high degree to the data contained in the BADs and the background field over the whole of the analysis area. The sequence of events is as follows:

(a) Analysis at 1000 mb—this provides a base for conversion of SIRS thickness values to contour heights.

(b) Analysis at 100 mb. The difference between analysed and observed heights is used to provide corrections to reported contour heights down to 500 mb as a technique for eliminating random errors between radiosondes, all values having previously been corrected for systematic instrumental differences.

(c) Analysis at 500 and 300 mb.

(d) The differences between background and analysis fields at the four levels so far analysed are used to modify background fields at the other analysis levels 200, 400, 700 and 850 mb. This is to obtain a certain amount of vertical consistency.

(e) These latter four levels are now analysed.

(f) Coefficients of the polynomials at the eight levels are now fitted three-dimensionally to give greater vertical consistency and to allow extraction of the fields at 900, 800 and 600 mb. (The forecast program uses for computation the analysis fields at 1000, 900, 800, 700, 600, 500, 400, 300, 200 and 100 mb.)

In current practice each level is analysed in three scans; the first uses heights only, the second uses heights and winds (if reported together), and the third uses all heights and winds. Data failing certain fitting tests will be rejected after each scan but will be tested again after the next scan. Weightings given to the data and the background vary with the density of data and the type of observation.

In order to produce a forecast to a schedule any forecaster, whether human being or computer, has to have a cut-off time by which analyses have to be begun regardless of what data may or may not have been received. Subsequently, 'retard' data for that analysis time will lead to an updating of the analysis. The computer uses this updated analysis as a basis for the background field for the next main hour. One important difference between the computer and the human is that the former uses data only at 0000 and 1200 GMT (plus or minus 3 hours for aircraft and satellite data) whereas the latter uses all the intermediate data. The possible introduction of a four-dimensional analysis system may rectify this in the future.

Intervention times. The latest times at which information can be fed into the computer at the various stages described above are 0230 or 1430 GMT for the fine-mesh rainfall (rectangle area) forecast, 0315 or 1515 GMT for the hemispheric coarse-mesh (octagon area) forecast and 1100 or 2300 GMT for the update analysis. Action to modify data before the first two of these times is known as pre-emptive intervention since the aim is to forestall or pre-empt problems that may cause poor analyses. Intervention before 1100 or 2300 GMT is usually done to correct known errors in the analysis obtained at the operational cut-off time but may also be used to pre-empt the effects of known retard data.

Intervention types. There are three types of intervention in use in CFO as follows:

Correction. There are two forms of correction procedure. The first is to combat errors in message format or corruptions in reception of messages, the second is to deal with random errors at isolated stations. For the first, messages from certain key stations are carefully scrutinized for errors beyond the capability of the data-bank quality-control programs to correct. From supplementary information such as a Part B of upper-air messages or inspection of other levels it may be possible to deduce correct messages. The corrected message is then broadcast for the benefit of other recipients as well as the synoptic data bank. The deduction of random errors may depend upon a number of factors, known developments, cloud pictures, continuity, intermediate data, preliminary manual analyses etc. The assessment of such errors will inevitably be subjective and,

particularly at the pre-emptive stage, may be in error. Correction of random errors is, therefore, effected by a message direct to the computer for use by the BADS. Corrections at the pre-emptive stage for the fine-mesh forecast may be amended before the main forecast and again, if necessary, for the update analysis.

Rejection. In areas where there are moderate quantities of data and an incorrect value may cause problems to the analysis program, rejection may be more appropriate than correction. Rejection may be used if an observation is known to be incorrect but there is doubt at the time what is the correct value. Rejection at this pre-emptive stage may be reversed later.

Bogusing. Where there is a sparsity of data at the analysis time but where, perhaps, using intermediate data, satellite pictures or other information the analyst is in a position to improve upon the background field at the pre-emptive stage or the operational analysis at the update stage then he may invent observations to ensure that the objective analysis is consistent with these other data. Bogus data inserted at the pre-emptive stage can be amended or deleted at the update stage.

Difference in emphasis—pre-emptive to update intervention. Before the operational forecast cut-off time the intervention team looks for possible errors in the background field that will not be counteracted by new data so that bogusing action can be taken. Otherwise the main intervention effort concerns the detection of message errors and random errors at key stations to deal with which the main tools are correction and rejection.

The timings of satellite orbits are such that pictures can be studied across most of the Atlantic area before the operational cut-off time and, on the basis of the information obtained, pre-emptive action taken on humidity, using bogusing techniques.

Between the operational and update stages charts are analysed manually in CFO at the surface, 500, 300 and 100 mb over the American–Atlantic–European sector of the hemisphere on the scale 1:20 million and over the whole hemisphere on the scale 1:30 million. Differences between manual and computer analyses are studied and reasons for differences investigated. Data received since the last cut-off are also examined and their probable effects on the update analyses assessed. Similarly, data for later times are studied for consistency with the analysis. Correction or rejection procedures may be applied to any data whether received before or after the operational cut-off. The main procedure likely to be employed at this time, however, is the addition of bogus data in areas where the objective analyses are considered to be in error.

With the exception of messages corrected, for format or corruptions, and fed to the data bank via the communication centre all intervention messages are read by the computer using punched cards. Intervention at the four levels surface, 500, 300 and 100 mb influences the remaining four analysis levels through the objective analysis scheme.

Possible future developments

Changes to schedules. The times by which forecasts are required by users are not always compatible with the production of the forecasts. Facsimile broadcast schedules and the requirements of civil aviation result in the operational analysis being used by the forecast suite before it can be vetted by CFO.

Despite the efforts of the intervention team the analysis will inevitably contain some features that may or may not be critical to a 24-hour forecast but are likely to lead to deterioration in longer-period forecasts. Within CFO itself, however, the times of output of 24-hour surface prognoses and synoptic reviews are such that the 36-hour forecast based upon 0000 or 1200 GMT is used as a basis for the 1200 or 0000 GMT 24-hour surface prognoses.

For CFO purposes it is intended within the near future to shorten the operational forecast to cope solely with the short-term requirements but to extend the update forecast to 84 hours. This will result in some improvement in the 36-hour guidance for the senior forecaster and may also give better guidance to the medium-range forecaster although here the effect of using a forecast based upon a superior analysis may be negated by having to use an 84-hour forecast instead of one for 72 hours for the day 3 guidance.

For the short-period forecasts some benefit would probably accrue if the user could wait a further 30 minutes to allow time for inspection and possible modification of the analysis by the intervention team.

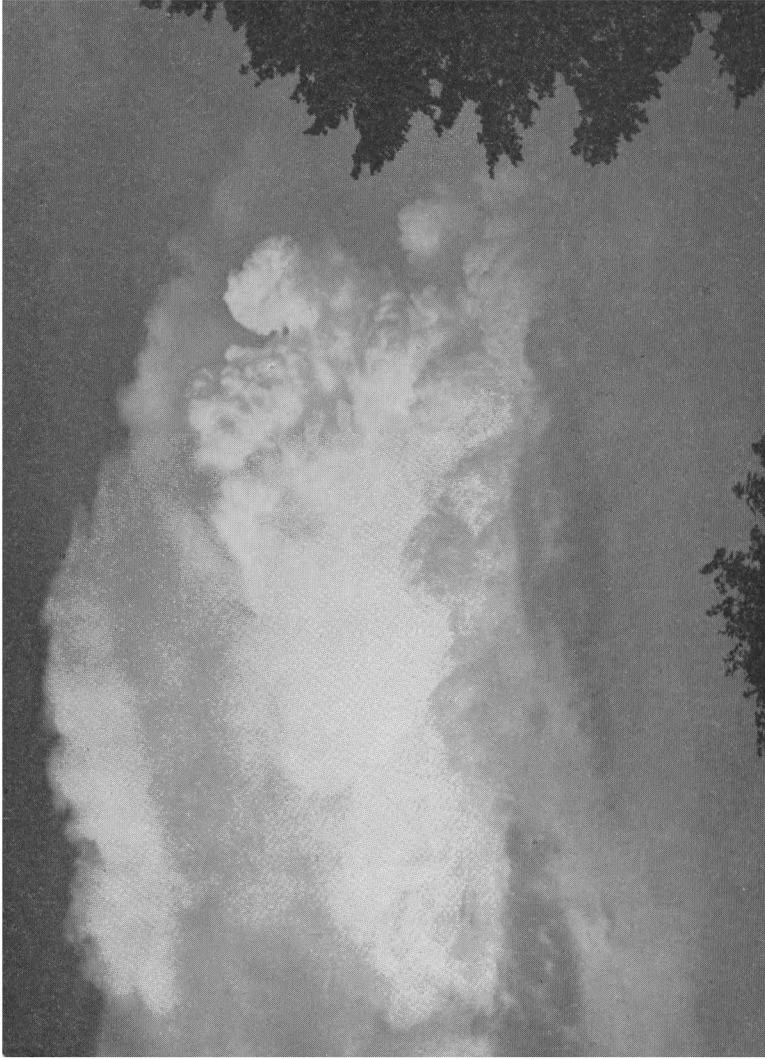
Use of visual display units. Owing to delays in punching and verification of cards for intervention input the cut-off is approximately 30 minutes before the start of the forecast suite. By use of a VDU and keyboard in CFO it is possible for the intervention team to submit messages direct to the computer for use by the BADS and so reduce the time between the intervention dead-line and the analysis program. This type of intervention is still indirect in that data are inserted in the hope that they will produce a required effect. Techniques are being developed, however, for use in CFO by which contour lines might be re-drawn directly on to a VDU. At present this method is available to modify the background field only but could possibly be extended to modify the operational analyses at a later date.

Intervention procedures using a VDU and keyboard to insert data and the background modification techniques are available to CFO on an operational basis but are still subject to further development. Their use is supplementary to the established punched card intervention methods and rather in the nature of field trials. It is probable that, in time, punched-card intervention will become a back-up procedure for the more sophisticated and faster VDU techniques.

Monitoring of the data bank. At present the synoptic data bank is filled at discrete intervals but there is only one print-out (after the start of the operational analysis) of data, both accepted and flagged. Some data contain errors that escape detection by CFO and some arrive too late for vetting. In order to make maximum use of all available data it will be necessary to have a continuous flow of data from the communication centre to the computer, with CFO being able to interrogate the data bank at any time for lists of data, accepted or flagged. Such information would be received in CFO on a VDU, printed, if necessary, on a thermal printer and corrections made by means of the VDU and keyboard.

Such monitoring would also enable CFO to know what data are in the data bank at the scheduled start of the forecast suite and to decide whether it would be worth a short delay to await the arrival of more information. It may even be desirable for control of all the operational programs—analysis, plotting, forecast—to be on command from the keyboard in CFO.

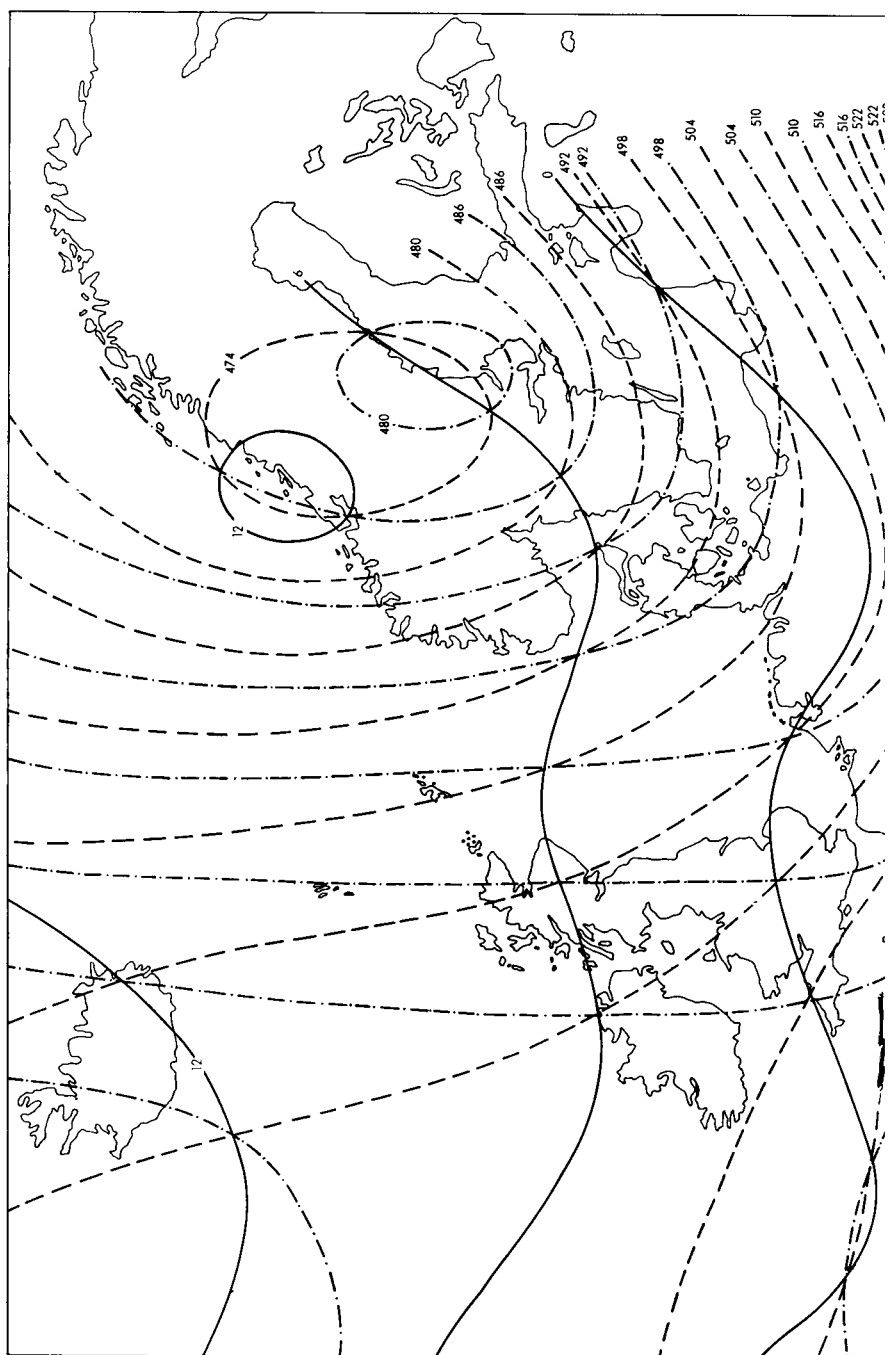
Satellite data. Humidity intervention might be possible in the future by using digitized satellite cloud data for direct input to the analysis program. Similarly



Photograph by C. J. Richards

PLATE I—HEAT THUNDERSTORM AFTER A FINE HOT DAY

The photograph was taken near High Wycombe, Bucks. at 1930 BST on 9 June 1970. Vigorous convection is evident within the cloud mass, with a recently formed anvil canopy spreading out from the cloud top.



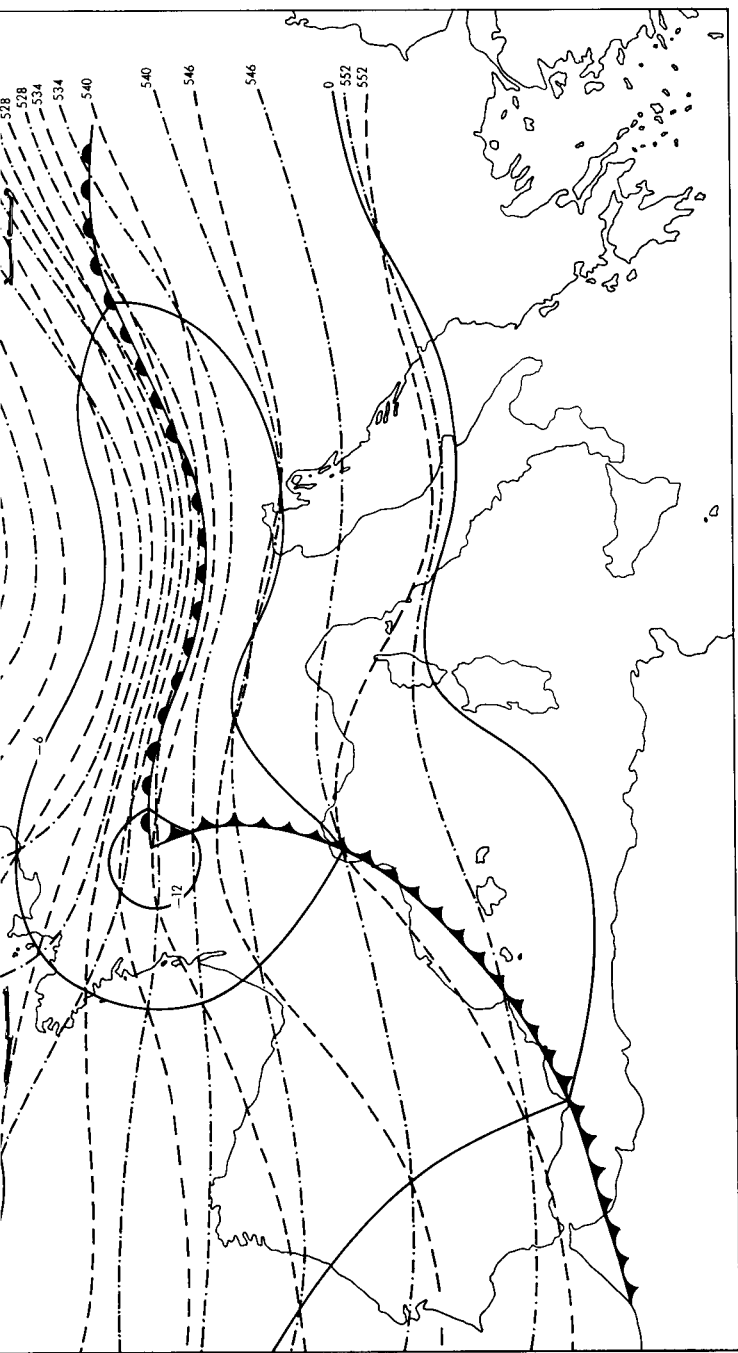


PLATE II—THREE-DIMENSIONAL SYNOPTIC WEATHER MAP FOR 28 DECEMBER
1783 AT 14 h

— 1000-mb contours
 - - - 500-mb contours
 - - - 1000-500-mb thickness lines
 Heights are in decametres.



Photograph by M. M. Rathore

PLATE III—PHOTOGRAPH OF LIGHTNING TAKEN AT BRACKNELL AT MIDNIGHT ON 8 AUGUST 1975, LOOKING EASTWARDS

satellite radiation data contain some information about total precipitable water and this, too, may be of use to the analysis program.

Improved manual analyses. Work is in progress with the object of using computer plotting techniques to give CFO extra data not at present available in plotted form. The two most important of these are charts on scales 1:10 and 1:15 million for the Atlantic and Pacific areas respectively to enable all ship reports received to be plotted on station even if this means using an abbreviated form of the report. Similar charts are also planned for analysis of aircraft and satellite wind reports, particularly for the intermediate times of 0600 and 1800 GMT. The intention is to try to obtain greater detail at the levels of greatest importance to the numerical forecast with particular reference to detail appropriate to the fine-mesh forecasts.

Feedback of information from CFO to programmers. The enlargement of the intervention team has had the immediate and beneficial effect of increasing the interchange of ideas between CFO and programming staff leading to steady improvements in the quality-control and analysis programs. As a consequence programmers are or soon will be investigating variations in techniques for using SIRS data, different weightings of data, methods of humidity intervention and improvements to quality-control techniques.

The philosophy of intervention. The need for human intervention in the increasingly automated processes surrounding quality control and analysis requires consideration both in practical and philosophical terms. On individual occasions the need for either update or pre-emptive intervention can clearly be demonstrated. However, there are occasions, at the pre-emptive stage especially, when transcription errors or errors of judgement occur, leading to worse analyses than would have otherwise occurred. It will be necessary to demonstrate unequivocally the effectiveness of both update and operational intervention probably by repeating in parallel the analysis programs without any intervention at all and with intervention only at the update stage. Improvement in the analysis techniques will gradually reduce the need for intervention and, probably, the evaluation programs mentioned above should be repeated periodically.

Experience of running forecasts without update analyses, when standby computer facilities are used, suggests that such exercises will indicate a continuing need for intervention. Should this state of affairs be accepted as a future necessity or should effort be concentrated on trying to program the human thought processes that constitute intervention? Such programs would undoubtedly be very unwieldy with some very complex logic and their development would be an extremely costly process in man-hours alone. The human analyst being able to study selectively data from all the various complex sources can build up an analysis piecemeal perhaps with the option of more than one possible solution until the arrival of a small amount of new data—one ship report, one satellite picture possibly—clarifies the position. In short the human analyst can employ judgement and experience and is able to exercise logic of a quality unlikely to be programmed in the foreseeable future.

Even if it were deemed worth while to attempt to program the functions of the intervention team the development of the programs would probably be overtaken by technological developments in the instrumental field such as improved satellite sensing techniques, remote-reading stations, the use of constant-level

balloons etc. It is suggested therefore that, although intervention methods will change, the need for intervention as an integral part of the operational objective analysis scheme, an apparent contradiction in terms, should be allowed for in any planning concerning CFO.

551.521.14(712.7)

A SPRING SINGULARITY IN GLOBAL RADIATION BENEATH OVERCAST SKIES IN THE CANADIAN PRAIRIES

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Summary. A study of seasonal variations in hourly global radiation beneath overcast skies detects an abrupt decline in its intensity in spring. This is attributed to changes in the multiple reflection of solar radiation between ground and sky.

Introduction. Inhabitants of the Canadian Prairies are familiar with a variety of optical effects which develop when cloud sheets form over snow-covered ground.¹ These optical effects are caused by the high reflectivities of fresh snow and cloud. When cloud is superimposed over snow there may be considerable multiple reflection of solar radiation between the sky and the ground, and the general effects of this are to cause a strong upward flux of solar radiation and to augment the downward flux with multiply reflected radiation. On rare occasions the intensity of the upward flux is almost as great as that of the downward and this causes the optical effect of white-out in which the visual perception of distance, size and location of objects is distorted. When the snow cover is broken by dark patches of water or bare earth, multiple reflection may selectively illuminate the base of the cloud so that an image of the ground is seen in the cloud. This phenomenon has been termed iceblink, cloud map or water sky in the Arctic where it is commonest. In the prairies multiple reflection is rarely manifest in such striking optical effects as white-out and iceblink, but it commonly augments the intensity of solar radiation beneath overcast days in winter. Indeed, this paper shows that the average hourly intensity of global radiation on overcast days at Winnipeg is greater in late winter than in midsummer.

The purposes of this paper are to compare seasonal variations of global radiation intensity at Winnipeg beneath clear and overcast skies and to focus attention upon an abrupt decline in the intensity beneath overcast skies in spring. This decline accompanies the spring thaw and is presumed to arise from a decrease in multiple reflection.

Multiple reflection. The process whereby solar radiation is reflected back and forth between the ground and the sky was first termed multiple reflection by Ångström and Tryselius.² Deirmendjian and Sekera³ used the term multiple scattering, and Möller⁴ used the term backscatter to denote the part of global radiation that is contributed by multiple reflection. The amount of multiple

reflection is apparent in the difference between actual global radiation G and the global radiation G_0 which would obtain over a perfectly black surface. The ratio between these G/G_0 is termed the intensification ratio. The magnitude of the intensification ratio depends upon the albedo of the ground a , and the reflectivity of the sky d . The actual global radiation can be treated as the sum of G_0 and an infinite series of reflected radiation terms:

$$G = G_0 + G_0 a d + G_0 a^2 d^2 + G_0 a^3 d^3 + \dots$$

This is a convergent series the limit of which is given by $(1 - ad)^{-1}$. Thus, Ångström and Tryselius showed that:

$$\frac{G}{G_0} = (1 - ad)^{-1}$$

and concluded that at Abisko ($68^\circ 21'N$, $18^\circ 49'E$) the intensification ratio typically ranges from highest values of 2.1 with overcast skies in winter, to lowest values of 1.02 with clear skies in summer.² Möller derived intensification ratios of 1.14–1.19 beneath overcast skies at Toronto, and of 1.46–1.60 beneath overcast skies at Moosonee in northern Ontario, Canada.⁴ Sawchuk calculated mean daily intensification ratios at Toronto between 1 January and 30 June 1970 and found that, with snow-covered ground, the ratio is usually between 1.5 and 3.0, and that, with snow-free ground, it is usually between 1.2 and 1.3.⁵ Thus, under favourable circumstances, multiple reflection may sustain an actual global radiation which is two to three times greater than that which would obtain over a perfectly black surface.

The process of multiple reflection has attracted the attention of climatologists endeavouring to estimate global radiation receipt from measured sunshine duration using linear regression equations of the form:

$$\frac{G}{G_a} = a' + b \frac{n}{N} \text{ where } G = \text{actual global radiation,}$$

G_a = intensity of solar radiation on a horizontal surface
at the top of the atmosphere,

n = actual duration of bright sunshine,

N = maximum possible duration of bright sunshine.

It seems that multiple reflection enhances G to such an extent in winter that pronounced seasonal variations in the coefficients a' and b are generated. This problem has been examined by Mateer,⁶ Bennett,⁷ and by Driedger and Catchpole.⁸

Data and method. The data described in this paper were observed at Winnipeg International Airport, a synoptic meteorological station operated by the Canadian Atmospheric Environment Service. The analysis examines hourly global radiation (direct plus diffuse solar radiation on a horizontal surface) observed by an Eppley 180° pyrheliometer between January 1961 and December 1965. Since a purpose of the analysis is to classify radiation according to sky conditions, hourly durations of bright sunshine, observed by a Campbell-Stokes sunshine recorder, are also used. A total of 21 900 pairs of hourly observations of global radiation and sunshine duration are analysed in this research. Throughout this paper time is given in Local Apparent Time (LAT).

The main purposes of the paper are to describe seasonal variations in global radiation beneath overcast skies in both absolute and relative terms. Overcast skies are arbitrarily defined as occasions when the duration of bright sunshine in a particular hour is equal to, or less than, $1/10$ hour. Likewise, clear skies are arbitrarily defined as occasions when the duration of bright sunshine is equal to, or more than, $9/10$ hour.

At the outset it was expected that the amount of multiple reflection might vary with time of day in response to diurnal variations in zenith angle and state of snow surfaces. Therefore, no attempt was made to amalgamate hourly data into daily totals, and the seasonal regimes of radiation observed at particular times of day were examined.

However, it was also expected that a period of only five years would be too brief for purposes of calculating mean hourly global radiation on each day. Consequently, the year has been divided into overlapping pentads to allow means to be calculated from larger samples than would otherwise have been the case. The first pentad is 1–5 January, the second 2–6 January and the third 3–7 January. This use of overlapping pentads has a smoothing effect upon the data illustrated in Figures 1 and 2.

In the first part of the analysis the 25 hourly observations of global radiation in each pentad are classified according to whether or not they were observed beneath clear or overcast skies. Pentad means of overcast and clear sky global radiation are then calculated for each hour.

In the second part, the mean global radiations with overcast skies are expressed as percentages of the maximum global radiations observed in the corresponding time intervals. The first part of the analysis examines absolute variations in global radiation beneath overcast skies and the second part examines relative variations.

Results. The voluminous nature of the results militates against their being presented in their entirety. Figure 1 contains seasonal variations of mean global radiation beneath clear and overcast skies for three hours, namely, 10–11, 11–12 and 12–13 LAT. Figure 2 contains mean global radiations expressed as percentages of the corresponding maxima. In this case the hours selected for exemplification are 09–10, 12–13 and 15–16 LAT. Figure 1 demonstrates that the seasonal regimes of global radiation beneath overcast skies are quite different from those beneath clear skies. The latter display the wide amplitude between a summer maximum and a winter minimum expected of a station located at 50° N. Before the middle of March the seasonal regimes of global radiation beneath overcast skies roughly parallel those beneath clear skies. However, in late March and early April there is a sharp decline in the mean intensity of global radiation beneath overcast skies. Throughout summer this mean intensity varies irregularly but, in general, values remain similar to those which obtain in February.

The hours selected for examination in Figure 1 are those occurring in the middle part of the day when absolute radiation intensities are greatest. Early morning or late afternoon hours are less suitable for illustrating seasonal regimes since they are nocturnal near the winter solstice. However, the results of this analysis show that this spring singularity is also apparent in the morning and afternoon. To illustrate this point Figure 2 contains data observed at widely separated intervals during the day.

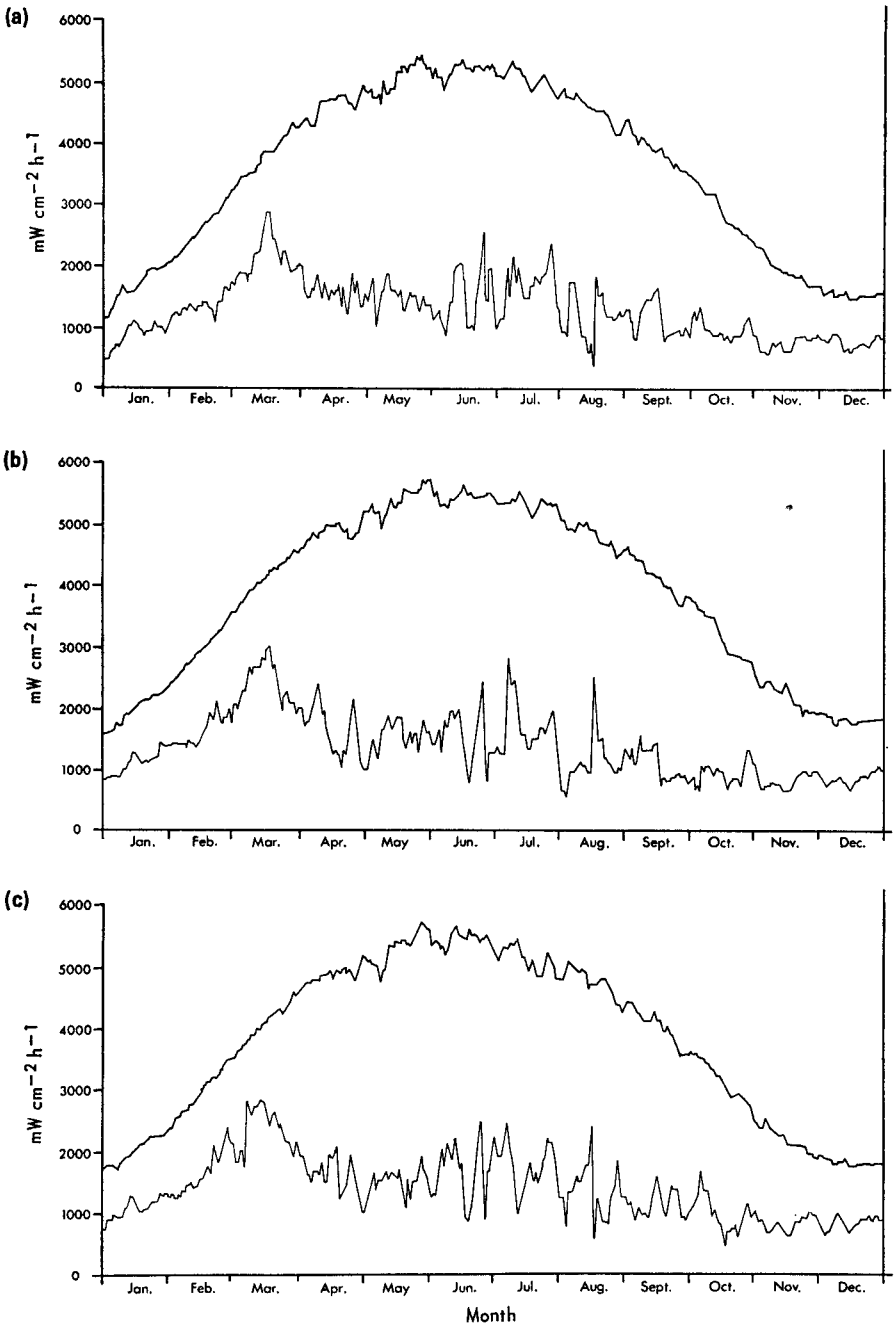


FIGURE 1—MEAN GLOBAL RADIATION AT 10-11 LAT (a), 11-12 LAT (b), AND 12-13 LAT (c) AT WINNIPEG, JANUARY 1961-DECEMBER 1965

The means are calculated in overlapping pentads and, in each graph, the upper curve refers to clear skies and the lower curve to overcast skies.

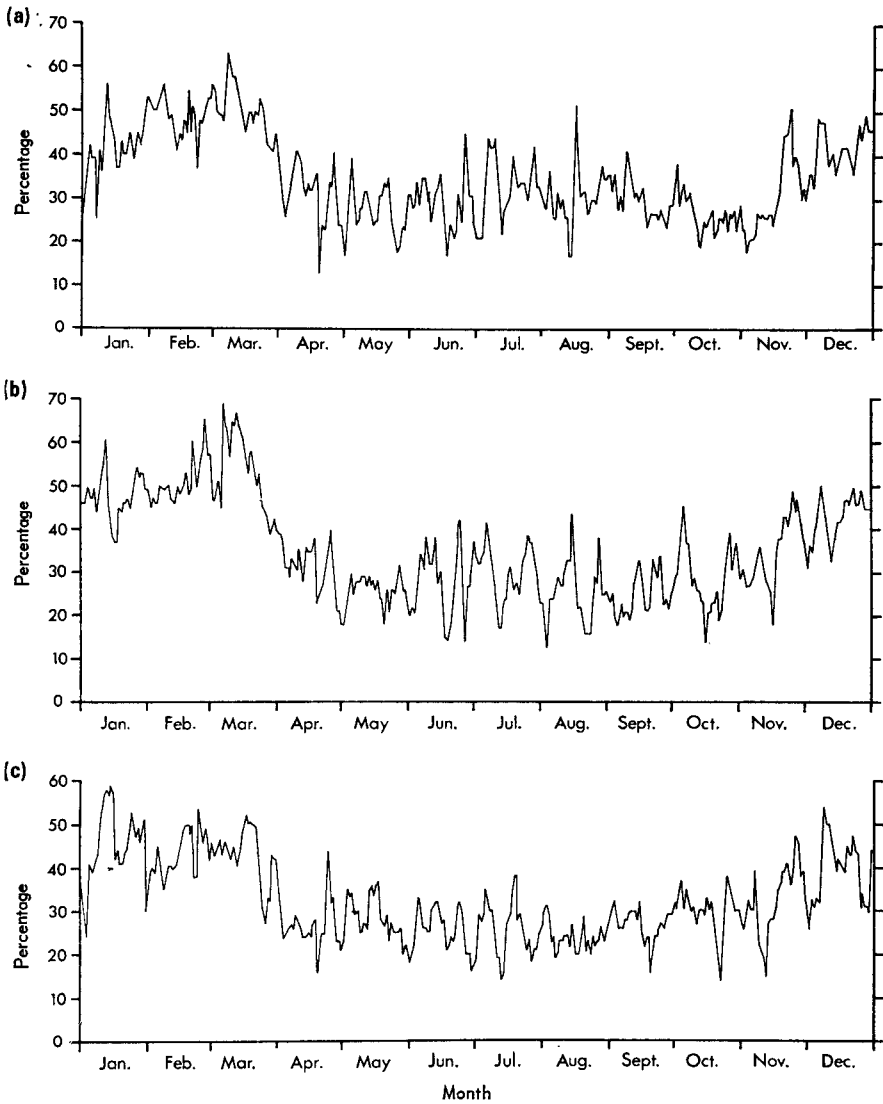


FIGURE 2—RELATIVE INTENSITY OF GLOBAL RADIATION BENEATH OVERCAST SKIES AT 09-10 LAT (a), 12-13 LAT (b), AND 15-16 LAT (c)

The relative intensities are calculated in overlapping pentads by expressing each mean global radiation with overcast skies as a percentage of the maximum observed in the appropriate pentad and hour.

Attention is first directed to Figure 2(b) since this is based upon the data in Figure 1(c). From November to February the global radiation beneath overcast skies is generally 40–50 per cent of the maxima observed in the corresponding time periods. In March this percentage rises to 50–70 per cent. Following a steep decline in the percentage in late March, values of 15–40 per cent persist until November when they rise to 40–50 per cent. Similar seasonal regimes are observed in Figures 2(a) and 2(c) but the spring singularity is somewhat less prominent in the earlier and later parts of the day.

Discussion. The outstanding feature detected by this analysis is the abrupt decline in absolute and relative amounts of global radiation beneath overcast skies in late March. This period of decline coincides roughly with the spring thaw of the snow cover at Winnipeg from 1961–65. Unfortunately, albedo is not measured at Winnipeg International Airport but the general features of the albedo change can be inferred from daily observations of snow depth. Kung *et alii* have shown that when the depth of snow exceeds 12.5 cm (5 inches) surface albedo remains high and does not vary with snow depth.⁹ When depths fall below 12.5 cm albedo declines and is directly related to snow depth.

During 1961–65 the median date on which the snow thickness declined to 12.5 cm was 30 March and the earliest and latest dates were 20 March and 6 April. The interval spanned by these dates coincides precisely with the period of decline in global radiation beneath overcast skies. In 1961–65 the median date on which snow was reduced to a trace was 7 April and the earliest and latest dates were 25 March and 19 April.

Although there is good circumstantial evidence that the spring singularity is caused by a decline in multiple reflection engineered by the spring thaw, this must remain a tentative conclusion. Hourly measurements of ground albedo are required to confirm this conclusion and hourly measurements of cloud parameters are required to show that this singularity is not caused by a seasonal change in cloud opacity.

Another feature of the seasonal regimes worthy of discussion is the absence in Figure 1 of an early winter singularity comparable to that observed in spring. It might be expected that the snow-cover development in November would modify global radiation beneath overcast skies in much the same way as does the spring thaw, but the regimes in Figure 1 contain no evidence of such a modification. Perhaps this contrast between the period of snow development and that of thaw arises from the fact that the former occurs close to the winter solstice when absolute values of radiation are low while the latter occurs at the equinox when global radiation is stronger. It is significant that the analysis of relative radiation intensities in Figure 2 does detect a rise to higher percentages in early winter.

An additional noteworthy feature of Figure 1 is that the global radiation on overcast days is much more variable than that on clear days and that this is especially the case in summer. In part this may be attributed to the fact that the Campbell–Stokes sunshine record gives a very restricted picture of cloud conditions. It cannot distinguish between clouds differing in form, density or elevation. Undoubtedly the radiation received on overcast days will vary as these parameters vary. However, a statistical explanation may account for part of the variability of global radiation beneath overcast skies. Thus, clear

skies are generally more common than overcast skies at Winnipeg and the latter are particularly rare in summer. This is illustrated in Table I using the sunshine durations observed between 12 and 13 LAT.

TABLE I—MONTHLY PERCENTAGE FREQUENCIES OF OVERCAST AND CLEAR SKIES BETWEEN 12 AND 13 LAT AT WINNIPEG, JANUARY 1961–DECEMBER 1965

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Overcast	37	31	27	31	30	18	17	14	31	25	50	47
Clear	44	53	56	54	53	59	63	66	56	62	33	44

The percentage frequency of each type of sky determines the number of cases which have been used to calculate mean global radiation in Figure 1. A percentage of 100 would indicate that all 25 cases in a pentad fall into a particular category. Only 14 per cent of August skies are overcast from 12 to 13 LAT. This indicates that each of the mean global radiations with overcast skies during August in Figure 1(c) is calculated from an average of only 3.5 values. The greatest variability in Figure 1 is shown by the curves of global radiation beneath overcast skies in June, July and August and in these months overcast skies are less frequent than in the remainder of the year.

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551.509.317:551.509.33:551.583.2

THE CONSTRUCTION OF 500-MILLIBAR CHARTS FOR THE EASTERN NORTH ATLANTIC–EUROPEAN SECTOR FROM 1781

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Summary. A method of constructing 500-mb charts for the eastern North Atlantic–European sector using historical daily weather maps from 1781 and inferred 1000–500-mb thickness patterns is described together with an illustrative example. The significance of extending a series of 500-mb charts over the past two centuries is discussed in relation to long-range forecasting techniques.

Introduction. Some uses of the series of daily synoptic weather maps for the eastern North Atlantic-European sector being constructed by the writer from 1 January 1781 have recently been discussed;¹ preliminary findings concerning British Isles Weather Types and PSCM indices for the 4-year phase 1781-84 have also been presented.^{2,3} A further synoptic use to which these charts could be subjected would be the construction of 500-mb contour charts using inferred 1000-500-mb thickness patterns.

The thickness of the 1000-500-mb layer has been synoptically analysed by European meteorological services on a routine basis since the introduction of reliable upper-air data in the 1930s, and the synoptic climatology of 1000-500-mb thickness lines is now adequately documented over the northern hemisphere for the past 30 years. Monthly charts giving mean and extreme maximum and minimum positions of standard thickness lines have been published for the period 1951-66.⁴

The various sources of surface data that are available from the latter part of the eighteenth century^{5,6,7,8} allow a confident analysis to be made of daily surface pressure patterns over the eastern North Atlantic-European sector from 1781, with standard isobars drawn at 4-mb intervals.

The object of this discussion is to show that it would be a feasible and worthwhile proposition to construct a series of 500-mb charts using historical daily synoptic weather maps from 1781 employing a method adapted from the well-established technique of preparing forecast thickness patterns.⁹

Method. The notation S_1 , S_2 ; L_1 , L_2 ; and T_1 , T_2 refers to two succeeding historical daily charts at 14 h and indicates respectively surface, 1000-mb and 1000-500-mb thickness patterns.

Construction of 1000-mb chart. A reasonable approximation to the contours on the 1000-mb chart could be obtained from selected surface isobars on the historical surface maps using the formula:

$$1000\text{-mb height} = \frac{3(p - 1000)}{4} \text{ geopotential decametres}$$

where p is the surface pressure in millibars.⁴

Construction of 1000-500-mb chart. The 1000-500-mb thickness pattern could be inferred by employing a combination of techniques:

(a) Spot values of the 1000-500-mb thickness at a network of points could be obtained as follows:

- (1) By assuming a saturated adiabatic lapse rate in the 1000-500-mb layer, an approximation of the 1000-500-mb thickness could be deduced from the relationship between total thickness and wet-bulb potential temperature, theoretical 1000-mb wet-bulb values having been extrapolated from actual surface temperatures and pressures plotted on the historical weather maps.
- (2) By using relationships between surface temperature and 1000-500-mb thickness determined from present upper-air data. Since thickness lines are advected as if embedded in the 1000-mb geostrophic wind field, an allowance for air-mass changes could be made by classifying the temperature/thickness relationship at each upper-air station according to the 1000-mb wind direction. The relationship could then be applied

to a network of actual or inferred surface temperatures and 1000-mb winds on S_1 , S_2 and L_1 , L_2 , etc. corresponding to the locations of present upper-air stations.

(b) Thickness lines could be advected from T_1 to T_2 according to the geostrophic wind field of L_1 , taking into account, as far as possible, continuity of frontal and air-mass analysis from S_1 to S_2 , nature of underlying surfaces and physical and dynamical processes.

(c) The resulting thickness pattern could be checked against the inferred spot-thickness values plotted on T_2 , see (a), and adjustments made if necessary.

(d) The employment of statistically derived relationships between certain 1000–500-mb thickness lines and surface weather, for example, critical total-thickness values associated with the change-over from liquid to frozen forms of precipitation,¹⁰ and those values related to the position of the Polar Front at different seasons.

(e) 1000–500-mb thickness patterns associated with characteristic surface situations could be inferred.

(f) Regions of intensification and discontinuity in the thickness gradient could be located with reference to positions of surface fronts.

(g) Adjustments could be made to ensure a mutual consistency between the 1000-mb and 1000–500-mb topographies from a knowledge of the actual intensification and movement of surface weather systems as described by the Sutcliffe Development Theorem.

(h) Time continuity could be maintained of daily positions of thermal troughs and ridges, cold and warm pools.

(i) The positions of thickness lines could be compared with the appropriate monthly means and extremes from the present synoptic climatological record, to ensure that exceptional displacements had not been made unless it was considered that the weather situation had been of an extreme type.

Construction of 500-mb chart. The 500-mb contour chart could now be constructed by gridding the 1000-mb contours with the 1000–500-mb thickness lines.

General survey. Finally all three constructed charts could be subjected to a general review to ensure, as far as possible, that the resulting patterns have an overall consistency in the light of synoptic experience with three-dimensional atmospheric circulations.

An illustrative example. By employing the method outlined above a three-dimensional representation of the synoptic situation for 28 December 1783 has been constructed (see Plate II).

Synoptic situation. From 27 to 28 December 1783 a depression moved slowly east from the Bay of Biscay into central France. A very cold east-north-easterly airstream covered the British Isles. On the 29th pressure rose over the British Isles and western Europe with the low-pressure system being transferred into northern Italy.

Weather. Occasional wintry showers occurred on the 27th with snow becoming continuous over south-eastern England on the 28th. Very mild air covered southern France on the 28th whilst clear but extremely cold conditions over Scandinavia were spreading south-west; -15°C was reported at both Stockholm and Spydberg, near Oslo, at 14 h. Heavy snow, freezing rain and glazed frost occurred in the frontal zone running west to east over the mainland of Europe.

1000–500-mb thickness pattern. The main features of the inferred 1000–500-mb thickness pattern are a confluent thermal ridge over France with a strong thermal gradient in the forward area and a cold pool over Scandinavia. The pattern closely resembles the characteristic thickness pattern associated with the formation of a warm-occlusion secondary depression or warm-front wave.¹¹

Conclusion. Three-dimensional studies of the general circulation support the view that temporal and spatial changes of climate over the surface of the earth are related to variations of flow in the upper troposphere. Investigations of atmospheric circulation anomalies are proving to be of great value with present techniques of long-range forecasting. A recent analysis of monthly mean 500-mb charts for the period 1945–72 has shown that circulation anomalies at the 500-mb level are of significant importance with the prediction of temperature and rainfall on the 15-day and 30-day and possible seasonal time scales.¹²

Studies of climatic change during the secular period have also suggested that anomalous modes of atmospheric circulation may have longer periods of characteristic persistency ranging over time scales of yearly to decadal dimensions. An attempt to construct 500-mb charts using inferred 1000–500-mb thickness patterns from historical weather maps before the routine synoptic analysis of upper-air charts would therefore have prospects of considerably lengthening the synoptic record of the three-dimensional representation of the atmosphere in which the search for monthly, seasonal and longer-period analogues could be extended. The determination of the frequency, duration and nature of possible long-term anomalies of atmospheric circulation over the past two centuries would provide a greater scope for anticipating the character of climatic changes in the future.

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REVIEWS

Waves in the atmosphere, by E. E. Gossard and W. H. Hooke. 250 mm × 170 mm, pp. xv + 456, *illus.*, Elsevier Scientific Publishing Company, P.O. Box 211, Amsterdam, The Netherlands, 1975. Price: Dfl. 156.00.

The main title of this book 'Waves in the atmosphere' is disappointingly inaccurate and much broader in scope than the actual subject matter, which is accurately described by the sub-title 'Atmospheric infrasound and gravity waves—their generation and propagation'. The authors deal with waves whose properties are dominated by the effects of atmospheric compressibility and gravitational stratification and only include first-order effects of the earth's rotation. Large-scale waves such as atmospheric tides, Rossby waves and Kelvin waves are not dealt with but some of their essential characteristics are noted when developing the basic equations.

The chapter titles are: Introduction; The fundamental equations; Relationships between field variables; Wave equations and dispersion equations; Some boundary value problems; Dynamic stability of atmospheric waves; Wave propagation in a dissipative atmosphere; Mountain lee waves; Infrasound; Progressive buoyancy waves in the lower atmosphere; Waves in the upper atmosphere.

The basic equations are derived from first principles in a clear and careful manner which should make the book self-contained and lead owners of the book to use this section as a basic text for other purposes. Readers with little experience in atmospheric physics or fluid mechanics should benefit from this approach but more experienced readers who jump to a particular point in the book may have to search backwards to confirm aspects of notation which have not been re-emphasized after their initial thorough introduction. Having developed the basic equations the authors make their way in the clear and systematic fashion indicated by the chapter titles through to general and atmospheric models involving gravity waves and infrasound. The material centres around the troposphere with a concise discussion of effects in the upper atmosphere. A good physical understanding is coupled with followable mathematics and it is a delight to be led so easily from the basic equations to the most recent literature.

The latter part of the book considers observations of gravity waves and infrasound in the atmosphere and goes on to discuss the possible sources of the waves. Faced with the very extensive literature on mountain lee waves the authors present a short selective review which fits in well with the rest of the book. It contains some detailed examples and a discussion of momentum transport by mountain lee waves. The chapters on infrasound, progressive buoyancy waves,

and waves in the upper atmosphere include a detailed discussion of the methods of observation which includes both the instrumentation and some of the more specialized aspects of data processing. A particularly noteworthy aspect of the book is the attention given to possible sources of waves, a vital aspect not always considered in sufficient detail.

In all, this first-class book will form an excellent basis to the study of atmospheric gravity waves and infrasound and, in the absence of another comparable book, will be especially welcome. It does not require much background in atmospheric sciences or fluid mechanics and its clear, well referenced workings from the basic equations to the recent literature will make the book equally valuable to the experienced worker and to the student.

P. J. MASON

Physics of drop formation in the atmosphere, by Yu. S. Sedunov. 245 mm \times 175 mm, pp. x + 234, *illus.*, (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1974. Price: £8.40.

The original volume of which this is a translation was published in Russia in 1972, but this delay is not significant in what has been for some time a relatively slow growth field.

There are three reasons which make it unlikely that this book will be purchased by more than a very few: it is a highly specialist work, it is difficult to read, and it is unrealistically priced.

The author claims that the book is 'not a survey of achievements in this field but rather an attempt at constructing a systematic model of growth by condensation of droplet population with reference to atmospheric features' so the book must be judged to some extent on these terms.

In fact, the treatment is highly theoretical and mathematical with relatively minor reference to the results and methods of laboratory or atmospheric studies. The comprehension of the work is hindered by an undisciplined riot of non-standard mathematical symbols used in very cumbersome equations. This is a pity, for the book is the end product of an immense amount of work which discusses many aspects of droplet growth very thoroughly.

After a brief introduction, the theory of growth of a single droplet by condensation is discussed with particular reference to the relaxation times of the various processes involved, and the limitation of Fickian diffusion theory within one mean free path of the droplet surface. Processes thought to be unimportant are listed; the list includes radiative transfer, now thought to be important in some situations.

The next chapter discusses condensation nuclei (CN) beginning with a brief survey of observational data on their size distribution and chemical composition, followed by a discussion of the equilibrium radius of a CN and the variation of CN spectra with increasing humidity. The author's labelling of a particle as a CN or a droplet depending on whether its radius is less than or greater than the critical value for a particular supersaturation does not seem to be a fruitful one to this reviewer.

Chapters 4 and 5 discuss the interaction of populations of growing droplets with supersaturation, and demonstrate the well-known narrowing of the droplet spectrum observed in many numerical models but not in the atmosphere—a discrepancy, the possible cause (or causes) of which is still controversial.

The book finishes with two chapters on the effect of turbulence on fields of temperature, liquid water content and supersaturation, and concludes that turbulence *within* the cloud considerably broadens the droplet spectrum—a view not shared by most cloud physicists.

There is no discussion of droplet growth by coalescence, which the title of the book might lead some readers to expect.

W. T. ROACH

Advances in satellite meteorology 2, N. K. Vinnichenko and A. G. Gorelik (editors). 245 mm × 170 mm, pp. vi + 148, *illus.*, (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1974. Price: £15.75.

This slim volume is a translation of a collection of papers which were originally published, under the title 'Satellite meteorology', in the U.S.S.R. in 1972. Both present and original titles are misleading. Those who expect to find a general treatise on satellite meteorology will be sadly disappointed while those with interests in microwave and Doppler radar techniques, who might find this book useful, could be excused for overlooking it.

The papers can be grouped under five general subject headings: microwave emission from rain and water vapour (six papers); microwave observations made from the satellite COSMOS-243 (two papers); emission from the atmosphere and clouds in the 8–12- μ m band (two papers); procedures for interpreting Doppler radar data (three papers); the use of satellite imagery for sea-ice surveys (one paper). Within each subject grouping the papers are only loosely related. No general review papers are included.

The papers on microwave emission are mostly of a rather detailed practical nature. They summarize the results from series of ground-based microwave-emission observations (wavelength range 0.8 to 3.2 cm) aimed at improving relationships between emission measurements and atmospheric conditions. The results might also provide a partial basis for the design of satellite microwave radiometer experiments. Some of the tables and diagrams may be useful for reference purposes. COSMOS-243, which was active in orbit for four days in September 1968, carried a set of microwave radiometers. Some of the data from this experiment are presented in a semi-quantitative manner which fails to illustrate the potential usefulness of a scanning microwave radiometer. The ground-based measurements of atmospheric and cloud emission in the 8–12- μ m region were made in a single wide spectral passband. Although reasonable values for the emissivity of cirrus are obtained, little information is given on the data used in the calculations and there is no mention of continuum absorption. The Doppler radar papers expound methods of data analysis which are claimed

to provide improvements in the accuracy of derived vertical velocities. The papers are all rather dated; the work was done in or before 1970 and none of the references to the literature are more recent than 1970.

This volume cannot be recommended to the general reader and its value as a reference work is limited.

D. E. MILLER

NOTES AND NEWS

Dr R. Hide—Special merit promotion to Chief Scientific Officer

It is a pleasure to record that Dr Raymond Hide has been granted promotion to Chief Scientific Officer under the scheme which permits the promotion of scientists of exceptional ability without any consequential change in their administrative responsibilities. Dr Hide was appointed to the Meteorological Office in 1967 as Deputy Chief Scientific Officer in order to establish, within the Office, a laboratory for fluid dynamic experiments with rotating fluids. This was a field of research in which Dr Hide had already established himself as one of the world's leading authorities by the experiments which he initiated in Cambridge in the early 1950s and continued subsequently at Chicago, at Durham and as Professor at the Massachusetts Institute of Technology.

Since Dr Hide joined the Meteorological Office he has led a small group of scientists and his laboratory has become one of the principal centres for the study of geophysical hydrodynamics. Under carefully controlled laboratory conditions, it has been possible to reproduce motions characteristic of phenomena of the atmosphere and oceans including the atmosphere of other planets. By varying the experimental conditions remarkable insight has been obtained into the fundamental dynamical factors controlling many different aspects of motions on the surface of planets and in their interior. Dr Hide's penetrating studies have had an important influence on the development of ideas on the nature of geophysical phenomena as diverse as Jupiter's red spot and the variations of the earth's magnetic field as well as on the circulation of the atmosphere.

J. S. S.

515.515.3

LETTER TO THE EDITOR

Comments on 'The tornadoes of 26 June 1973'

Dr Fenner¹ concluded that the best prediction of severe storm movement was the mean wind shear direction. Spillane and McCarthy² give a theoretical basis for estimating trajectories in the downdraught of a thunderstorm and temperatures along these trajectories. They conclude that 'the organization and thus the

severity of the storm depends critically on the shear of the wind from the surface to about 450 mb'. They also state that 'a criterion for stability of the mature stage is that equal quantities of air are brought into the open system by the downdraft and updraft'.

Colquhoun,³ independently of Dr Fenner and on the basis of Spillane and McCarthy's work, postulated that the 'maximum storm intensity is reached when it moves with a velocity giving the maximum rate of inflow of air to the updraft/downdraft system from those components of the environmental flow parallel to the storm path'. By using the wind profile in the environment of the storm between the surface and 450 mb the velocity of the severe storm may be estimated. Testing the theory on nine storms which occurred in Australia and in the U.S.A. gave encouraging results. Comparison of the observed and forecast severe storm velocities showed an average absolute direction error of 5.6 degrees and average absolute speed error of 1.5 knots.

Using this method on the data in Figure 7 of Whyte⁴ gives estimates of the severe storm velocity of 240° 16 kt based on Crawley winds and 220° 15 kt based on Hemsby winds.

In most cases the direction of severe storm motion produced by this method will be similar to Dr Fenner's 'mean wind shear direction'.

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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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A NOTE ON THE ACCURACY OF RAINFALL FORECASTING USING EXISTING TECHNIQUES IN THE RIVER DEE CATCHMENT AREA

By C. A. NICHOLASS

Summary. Rain data collected as part of the Dee Weather Radar Project over a two-year period have been used to test the accuracy of some existing forecasting techniques. It is shown that the method of Holgate has a fairly high success rate, and that of Lowndes is able to predict heavy rain from westerly types but is less successful with predictions of heavy rain from other types in summer. The method of Benwell is reasonably successful in predicting very heavy frontal rain, but is not applicable to the more frequent, less heavy rainfalls.

Introduction. Recently there has been increasing interest from hydrologists in improved accuracy of forecasting areal rainfall over river catchments and subcatchments (see for example Dee Weather Radar Project, Operations Systems Report¹). The analysis in this note shows the accuracy which is at present attainable in parts of the River Dee Catchment using three rainfall forecasting techniques.

Techniques investigated. Holgate² described the synoptic rules used at the Main Meteorological Office at Preston to forecast rainfall for a number of areas in north-west England and North Wales. The forecasts of rain amounts for the Dee Catchment above Bala are divided into three categories, 5–15 mm, 15–30 mm, and more than 30 mm each within a 21-hour period. The accuracy of these forecasts has been investigated for the period from 1 April 1972 to 31 March 1974 using data collected from the relevant part of a network of 63 rain-gauges distributed over 1000 km² of the River Dee Catchment, which were installed by the former Water Resources Board as part of the Dee Weather Radar Project. These data provided a unique opportunity for assessing the techniques.

Lowndes^{3,4} has defined the meteorological conditions which should exist if heavy rain is to be expected in the River Dee area. The accuracy of his rules is investigated.

Benwell⁵ showed that the jet stream at 500 mb could be used as an indicator of very wet days (days with more than 63.5 mm). Although the number of days with such large amounts is small in the two-year period, on these and other wet days the position of the 500-mb jet stream has been investigated.

Results

Rainfall forecasts for the Dee Catchment above Bala, issued by the Meteorological Office (Holgate²). Forecasts for the Dee Catchment above Bala (see Figure 1) are issued as routine by Preston Main Meteorological Office. 'No forecast' implies that less than 5 mm of rain is expected. The synoptic rules used to make these forecasts are summarized in Holgate's paper.

The areal rainfall over the Dee Catchment above Bala has been computed using the interpolation techniques of English.⁶ To allow for slight timing errors in the forecasts, the areal rainfall was also calculated for periods displaced by both plus and minus three hours from the issued forecast period.

Table I is a contingency table of forecast and actual rainfall during the period from April 1972 to March 1974, taking the best of the three possible forecast periods. Forecast periods when snow fell or was lying in the gauges, thus making the rainfall estimates unreliable, have been excluded. Also shown in the first column are the occasions when no forecast was issued but more than 5 mm of rain fell.

The table shows that the correct category of rainfall event (excluding forecasts of less than 5 mm) was predicted in 100 out of 198 forecasts issued. Additionally the rain which occurred was within one category of that which was forecast on 193 out of 198 (97 per cent) occasions. However, on three occasions more than 15 mm of rain fell when no event was forecast. The table does not show the large number of forecasts of less than 5 mm, the vast majority of which were correct.

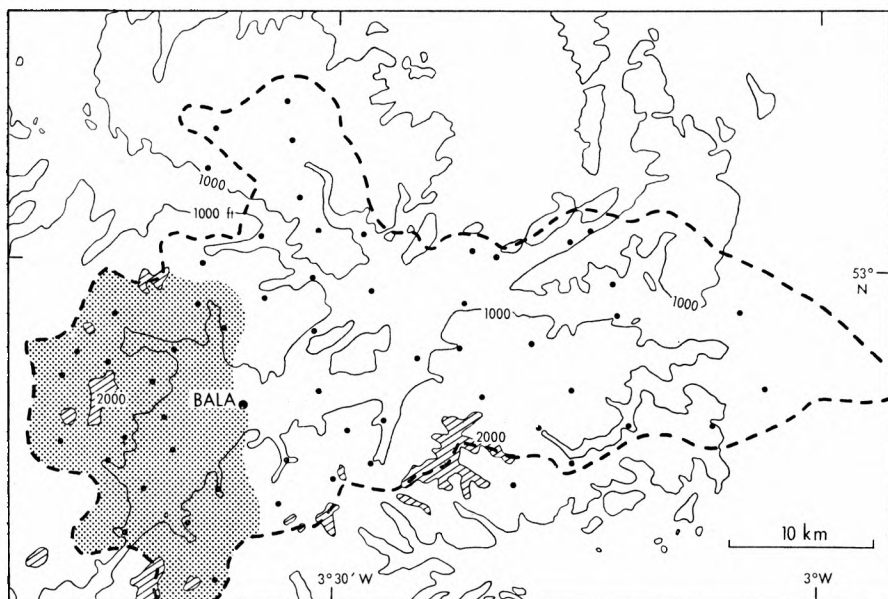


FIGURE 1—LOCATION OF RAIN-GAUGES IN THE DEE CATCHMENT AREA

The area above Bala is stippled. Contours are 1000 and 2000 ft above sea level (approximately 305 and 610 m). Hatching shows land above 2000 ft.

TABLE I—SUMMARY OF PRESTON FORECASTS FOR THE DEE CATCHMENT ABOVE BALA, 1 APRIL 1972–31 MARCH 1974

Actual rainfall	No forecast	Forecast rainfall			Total
		5–15 mm	15–30 mm	30 mm	
<5 mm		43 (53)	4		47
5–15 mm	32	70 (60)	20	1	123
15–30 mm	3	17	27	2	49
>30 mm			11	3	14
Total	35	130	62	6	233

The figures in brackets show the changes to the table which result if no allowance is made for timing errors.

The figures in brackets in the table (column 2) show what results would have been attained had no time correction been applied. It is apparent that timing errors of 3 hours are not a significant problem with these forecasts.

The range of rainfall amounts in each category is an important factor influencing the high success rate of this forecasting technique. However, it should be emphasized that this success rate was achieved in routine forecasting, whereas the other two techniques investigated below are verified against the observations and not forecast indicators.

Forecasting heavy rainfall in the Dee area using Lowndes's criteria. Lowndes has specified the meteorological conditions which should be satisfied if heavy rainfall is to occur at any point in the Dee Catchment area. He defined heavy rainfall as more than 50.8 mm (2 in) in winter (September to February inclusive) and more than 38.1 mm (1.5 in) in summer (March to August) falling in a rainfall day (09–09 GMT). Using 'readily available data' Lowndes analysed 16 occurrences in 55 winters and 45 occurrences in 57 summers.

He specified seven conditions which should be satisfied if heavy rain is to accumulate from westerly weather types. The summer and winter conditions show detailed variations, but they are broadly similar. Also, for summer rain he defined five conditions which should be satisfied for heavy cyclonic rains, with or without thunder, to occur.

Lowndes's criteria have been investigated using data from the entire Dee rain-gauge network. Because of the greater density of gauges compared with those available to Lowndes, heavy rainfall days were relatively more common—5 in winter and 11 in summer in the two-year period. Table II shows the number of criteria which were satisfied on these occasions. If it is assumed that 5 out of 7 criteria (or 4 out of 5 for summer cyclonic rains) should be satisfied before a forecast is issued, and if the criteria themselves were correctly forecast, then 4 out of 5 winter, and 4 out of 6 summer westerly occurrences would have been correctly forecast. However, none of the heavy cyclonic or thundery rains would have been correctly forecast.

For all other days in the two-year period, the number of days when 5 out of 7 criteria for westerly (or 4 out of 5 for summer cyclonic) rain were satisfied and the maximum 24-hour point rainfall on these days are shown in Table III.

To summarize Tables II and III, if a 24-hour rainfall total greater than 1 in (25.4 mm) is considered to be a wet day, then out of the 36 days when 5 out of 7 criteria for westerly types and 4 out of 5 for summer cyclonic types were satisfied, 28 were wet days. It should be noted that the method has been assessed using observations rather than forecast indicators.

TABLE II—RAINFALL DAYS EXCEEDING 50.8 mm IN WINTER AND 38.1 mm IN SUMMER

Type	Date	Maximum 24-h rainfall total	Number of Lowndes's criteria satisfied
		mm	
Winter westerly	9/11/72	62.2	6 out of 7
	2/9/73	67.2	5 out of 7
	9/11/73	63.4	3 out of 7
	4/1/74	60.4	6 out of 7
	29/1/74	74.6	5 out of 7
Summer westerly	28/4/72	49.4	7 out of 7
	26/5/72	49.0	0*
	3/7/72	51.6	6 out of 7
	1/4/73	51.4	7 out of 7
	12/5/73	39.8	4 out of 7
	5/8/73	80.2	6 out of 7
Summer cyclonic or thundery	9/6/72	39.8	3 out of 5
	31/7/72	66.2	3 out of 5
	15/7/73	53.2	3 out of 5
	31/7/73	52.6	0†
	27/8/73	52.6	0†

* Showery westerly

† Isolated thunderstorms

TABLE III—RAINFALL ON OTHER DAYS WHEN THE LOWNDES'S CRITERIA WERE SATISFIED

Type	Total number of days	Number of days with specified rainfall totals	
Winter westerly	14	≥ 38.1 mm	6
		25.4–38.0 mm	6
		< 25.4 mm	2
Summer westerly	7	≥ 25.4 mm	5
		< 25.4 mm	2
Summer cyclonic	7	≥ 25.4 mm	3
		12.7–25.3 mm	1
		< 12.7 mm	3

Use of the 500-mb jet stream as a predictor of heavy rain. Benwell, after investigating occurrences of more than 63.5 mm (2.5 in) falling at a point within a rainfall day concluded that two criteria connected with a jet stream at 500 mb should be satisfied if heavy frontal rain was to occur. The criteria were not defined specifically for the Dee Catchment but for North Wales as a whole (and other areas). He evaluated his criteria by seeking falls of heavy intensity (greater than 4 mm per hour) at *Daily Weather Report* stations in areas satisfying the criteria. This approach has not been used in this note. Instead, the three occurrences of frontal rain of 63.5 mm or more in a rainfall day have been identified from Table II, and the positions of jet streams on these days investigated. Of the three days, two had jet streams with wind speeds greater than 70 kt at 500 mb near or over Wales and the other had a wind of 65 kt. However, the position of North Wales with respect to the exit of, or a perturbation within, the jet stream at the time of the heavy rain, was hard to judge.

If all days in the two-year period when more than 38.1 mm (1.5 in) of frontal rain fell are examined, it is found that on 16 out of 19 days there is a 500-mb jet stream with wind exceeding 70 kt affecting one or more of the radiosonde stations in the United Kingdom. In many cases, the jet stream was not directly over Wales, nor was the perturbation or left-exit criterion

obviously satisfied. This association of wet frontal systems with 500-mb jet streams is well known, but it does not lead to the conclusion that whenever a jet stream is present, heavy rain will result.

The limitations of this technique are that it is only intended to predict very heavy point rainfall totals from frontal systems and not areal falls, and it requires accurate forecasts of the shape and position of the jet streams.

Conclusion. The rainfall forecasts, which are issued in real time using Holgate's rules, show significant success in predicting areal rainfalls over a part of the Dee Catchment.

The techniques of Lowndes and Benwell are often successful in predicting wet days from frontal systems moving from the west, which give a high proportion of the annual rainfall in the area, but neither fulfils the hydrological requirement of areal rainfall forecasts. Both methods have the limitation of not attempting to predict lesser rainfall totals which can be hydrologically important in winter, and Lowndes's technique shows little success in predicting the heavy summer cyclonic or thundery rains which can lead to flash floods.

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551.510.522

THE DEVELOPMENT OF THE ATMOSPHERIC BOUNDARY LAYER: THREE CASE STUDIES

By L. G. CHORLEY, S. J. CAUGHEY and C. J. READINGS
(Meteorological Research Unit, Cardington)

Summary. Values of the surface sensible-heat flux for specific periods are deduced from a series of temperature profiles (tethered balloon-sonde data) on each of three separate days. These flux values are compared with those obtained by more direct means using radiation, soil flux, evapotranspiration and Cardington turbulence probe measurements. Large-scale subsidence and advective effects and the application of a 'rate equation' to predict the lifting of an inversion due to heating from below are briefly discussed.

Introduction. Early theoretical work, for instance that by Ball,¹ and later experimental studies such as those of Rayment and Readings² have shown the need to study the development of the boundary layer below an overhead inversion. Such studies should ideally monitor the morning erosion of the

nocturnal inversion and the ensuing convective development (with possible interaction between this and an overhead inversion) which dies away in the evening as the surface inversion is re-established. However, it must be admitted that, on many occasions, this ideal diurnal cycle will be only partially realized. The work described in this paper concentrates on the evaluation of the vertical heat flux at the surface and compares the results obtained from the three methods for two of the cases considered. A test of the applicability of a rate equation, for predicting the rise of inversions during dry convection, is also described.

The observations discussed here were made at Cardington during August and September 1973. On three days in this period the Balthum (tethered balloon) sonde³ was used to provide temperature and humidity profiles. Sensible heat-flux profiles were deduced by downward summation of the flux divergences (see for example Cattle and Weston⁴) over 5-mb layers (the vertical eddy flux of potential temperature, $\overline{W'\theta'}$, was assumed to be zero above the level of the inversion top and no allowance was made for subsidence). Surface values of sensible-heat flux, Q_H , were also evaluated by the residual technique (see for example Munn⁵) that is to say $Q_H = Q_N - (Q_G + Q_E)$, the values of net radiation, Q_N , soil flux, Q_G , and evapotranspiration Q_E , having been continuously monitored at Cardington by a net radiometer, soil-flux plates and a lysimeter respectively. On two of the days $\overline{W'\theta'}$ was also measured directly using a Cardington turbulence probe mounted on top of a Clarke mast at a height of 16 metres (Readings and Butler⁶).

The three cases

24 August. Generally anticyclonic conditions prevailed during 24 August with a high 'cell' over the southern North Sea and a ridge over the British Isles. However, the upper cloud thickened at times and this explains the variation in the net radiation as shown in Figure 1. No major air-mass discontinuities were shown on the synoptic charts but the routine radiosonde ascents for the 24th indicated that small advective changes may have been occurring.

The sequence of potential-temperature profiles derived from the Balthum ascents on this day is shown in Figure 2. These four profiles indicate the changes which occurred as the nocturnal inversion was steadily 'warmed out' by surface heating as convection developed. The base of this inversion was lifted from 28 mb above ground level (AGL) at 0838 GMT to 44 mb AGL at 1031 GMT and by 1654 GMT convection was established throughout the layer monitored by the Balthum, i.e. θ is approximately constant on the 1654 plot in Figure 2.

Before applying the summation technique to the temperature profiles an attempt was made to allow for the presumed warm advection indicated above the level of 40 mb AGL (0838–1031 GMT). This was done by adjusting the 1031-GMT plot to become approximately aligned with the previous (0838) plot above 44 mb AGL. (Values of sensible-heat flux evaluated from the original unmodified profiles were large when compared with the probe and energy-balance values. It is possible that an instrumental error was responsible for this apparent warming.) The final profiles of sensible-heat flux are reproduced in Figure 2 (inset) and show the expected decrease of heat flux with

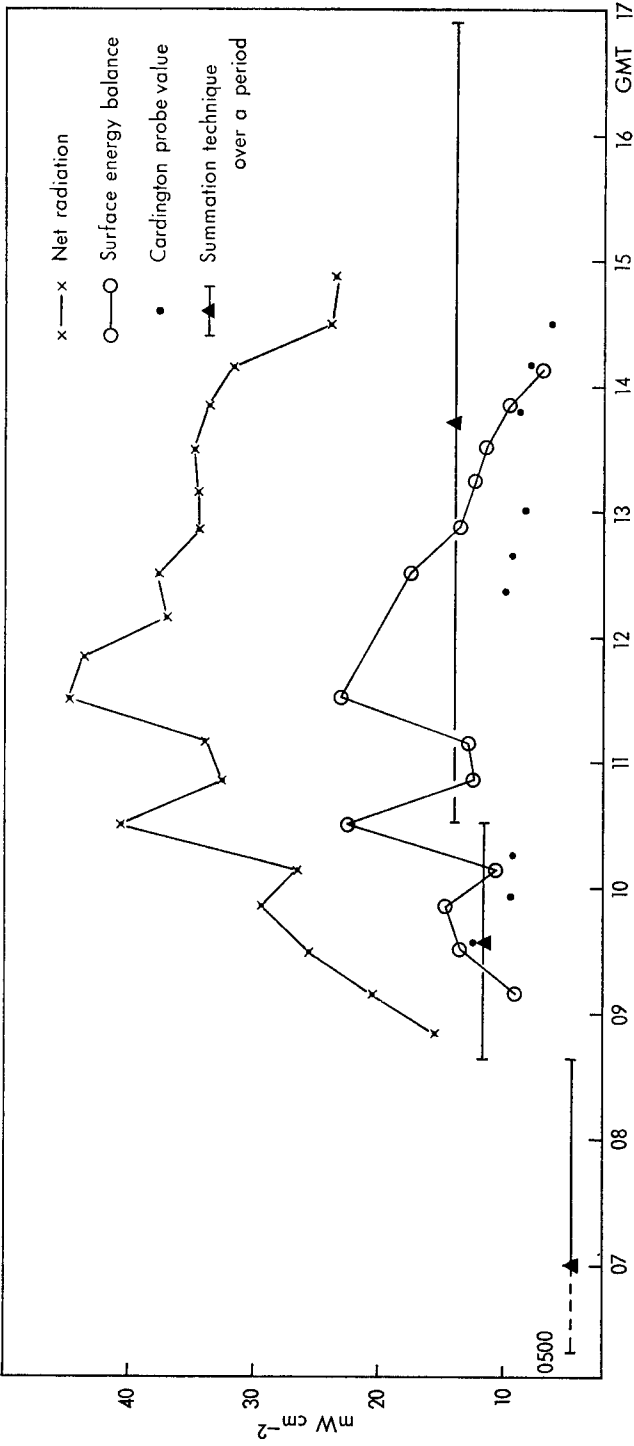


FIGURE 1—NET RADIATION AND SENSIBLE-HEAT FLUX ON 24 AUGUST 1973

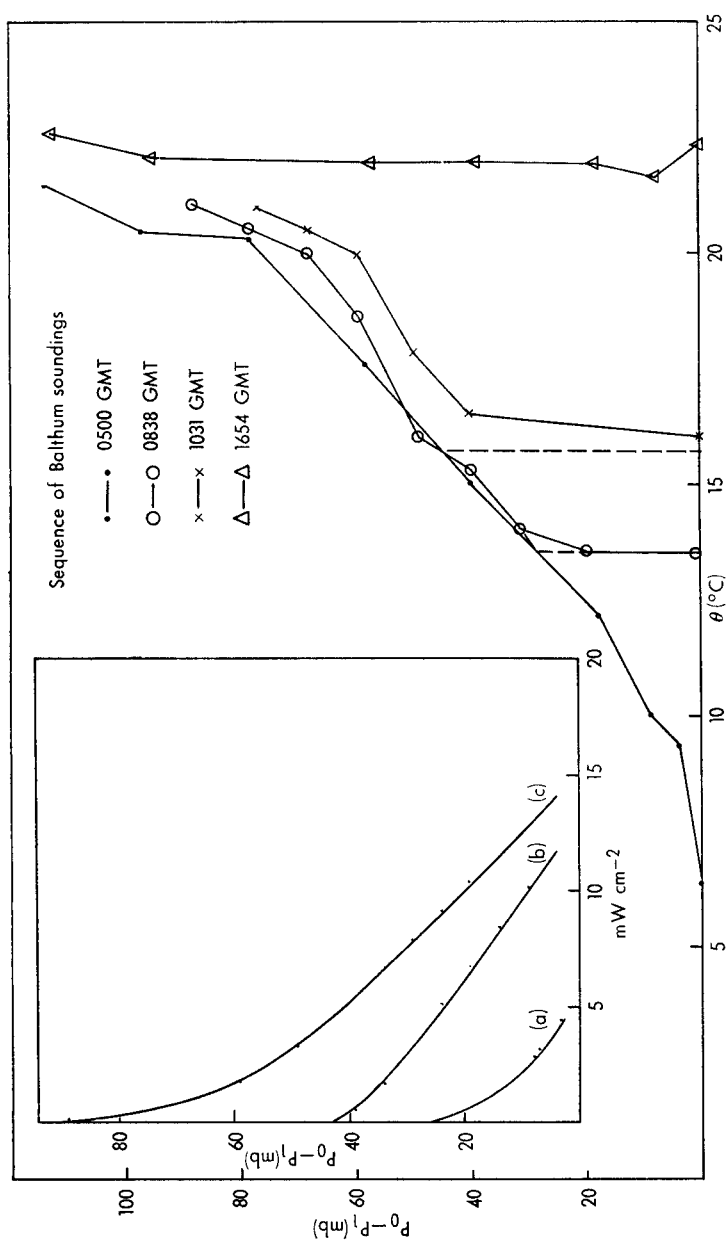


FIGURE 2—PROFILES OF POTENTIAL TEMPERATURE, θ , ON 24 AUGUST 1973

$P_0 - P_1$ is height above the surface in millibars.

Inset shows upward sensible-heat flux in milliwatts/square centimetre.

Summation values for periods between successive soundings, (a) 0500–0838 GMT, (b) 0838–1031 GMT, and (c) 1031–1654 GMT.

height. Values of sensible-heat flux (near the surface), obtained by all three methods described in the previous section, are shown in Figure 1. Reasonable agreement is indicated and the simple correction for advection, discussed above, seems justified.

The following equation (see Carson and Smith⁷) can be used to predict the rate of rise of an inversion (ignoring the effects of entrainment and the vertical velocity):

$$\frac{dZ_i^2(t)}{dt} = \frac{2\overline{W\theta_s}(t)}{\frac{d\theta^+}{dz}}$$

where Z_i is the height of the inversion base, θ^+ is potential temperature above the inversion base, and $\overline{W\theta_s}$ is the surface heat flux (the latter were taken as means of the probe values for the time intervals considered). An estimate of $d\theta^+/dz$ was obtained from Figure 2.

Using the appropriate values of Z_i , $\overline{W\theta_s}$ and $d\theta^+/dz$ for the period 0838 to 1031 GMT (i.e. the actual times at which the Balthum indicated the inversion base) the calculated rate of rise of the inversion is 5.6 mb/h compared with a measured rate of 6.1 mb/h. This order of disagreement falls well within the value corresponding to the tolerances on Z_i , $\overline{W\theta_s}$ and $d\theta^+/dz$.

7 September. During this period anticyclonic conditions were maintained over England; the anticyclone which was centred near the Channel Isles at 0000 GMT on 7 September changed little during the subsequent 24 hours. The routine radiosonde reports were studied to see if there were any discernible advective or subsidence effects in the light westerly airstream. The horizontal wind field and temperature distribution implied negligible advection in the 850–900-mb layer, the flow being nearly along the isotherms. Isentropic analysis methods were applied to this layer and the estimated subsidence for the Cardington area (period 0000 GMT to 1200 GMT on 7th) was 1.5 ± 1 mb/h compared with an estimate of ‘zero to 5’ mb/h obtained from the vertical-motion charts available at Bracknell. The conclusion that some subsidence was occurring is consistent with a lowering of the main temperature inversion during the 24 hour period (0000 GMT on 7th to 0000 GMT on 8th) shown on the Crawley, Sussex and Hemsby, Norfolk soundings: from 868 to 926 mb (2.4 mb/h) and from 850 to 896 mb (1.9 mb/h) respectively.

At Cardington fog had occurred overnight (6th–7th) and 7 to 8 oktas of stratus cloud, base about 100 m, was advected from the west at 0805 GMT. This cloud lifted rapidly at 1000 GMT and dispersed at about 1100 GMT. Skies thereafter remained clear apart from 1 okta of shallow cumulus, base 600 m, at 1500 GMT.

The sequence of potential-temperature profiles for this day (from the Cardington Balthum) is shown in Figure 3. The 0715 GMT sounding gives some indication of an upper inversion with a surface (nocturnal) inversion which was considerably modified by low-level cooling at 0833 GMT (associated with the advection of the low stratus cloud). This nocturnal inversion then lifted progressively, the base being at about 40 mb above ground by 1116 GMT. The next sounding (at 1241 GMT) shows an inversion base 77 mb above the surface, i.e. at 945 mb (it is suggested that this was the higher synoptic inversion

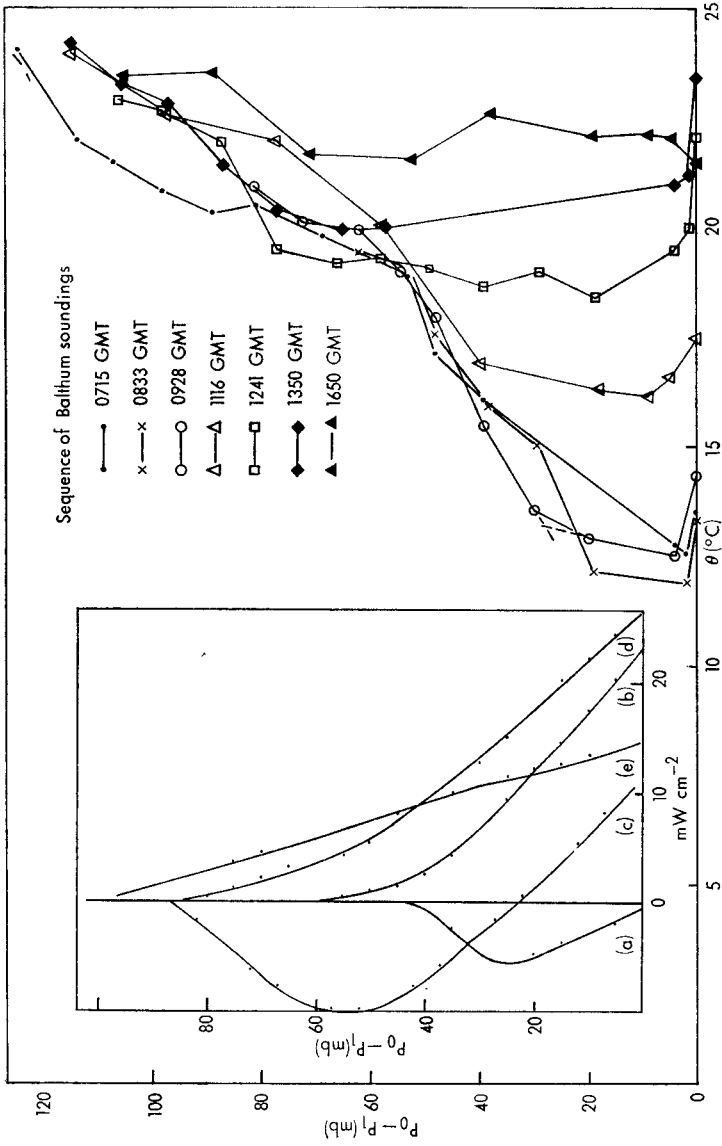


FIGURE 3.—PROFILES OF POTENTIAL TEMPERATURE, θ , ON 7 SEPTEMBER 1973
 $P_0 - P_1$ is height above surface in millibars.
Inset shows upward sensible-heat flux in milliwatts/square centimetre.
Summation values for periods between successive soundings, (a) 0833-0928 GMT, (b) 0928-1116 GMT, (c) 1116-1241 GMT, (d) 1241-1350 GMT, and (e) 1350-1650 GMT.

which was not affected by the heat flux from below and which is shown at 71 mb above the surface on the 1650 GMT sounding). This lowering of the synoptic inversion corresponds to a subsidence rate of approximately 1.5 mb/h which may be compared with the similar rates previously quoted. It follows from this interpretation of the data that the lower inversion was completely eroded by 1241 GMT.

Shown in Figure 3 (inset) are the profiles of sensible-heat flux. The early downward flux may reflect the evaporative cooling and radiation from the cloud layer, factors which would vitiate the summation technique. The flux shown by curve (b) for the period 0928–1116 GMT is entirely positive and is followed by a marked decrease of surface sensible heat (curve (c)) accompanied by a large negative value about 40 mb (maximum downward flux at about 54 mb) probably reflecting the erosion of the nocturnal inversion. Thereafter the fluxes are entirely positive. The decrease in surface sensible heat flux towards midday is difficult to explain satisfactorily. However, the trend does agree with that from the other estimates, and a considerable amount of evaporation did take place during the late morning. The values of the surface flux of sensible heat obtained by all three methods are compared in Figure 4, which shows also the net-radiation curve and the downward flux of sensible heat. It may be noted that the second peak in the sensible-heat flux plot is not reflected in the plot of downward flux; presumably because by 1241 GMT the lower inversion was no longer present and the fluctuations in net radiation values before 1000 GMT were probably due to the variations in the stratus cloud cover (and presumably cloud thickness). Net radiation and sensible-heat flux increased markedly as the cloud dispersed. Heat-flux values derived from the Cardington probe measurements are unfortunately not available for the period 1100–1200 GMT but the general conclusion that there were two maxima in the sensible-heat flux curve (i.e. near 1020 GMT and 1300 GMT) is supported by the available data.

Changes in water content (below the main inversion at 77 mb) were also examined. An increase of 0.208 g/cm² occurred during the period 0833–1350 GMT compared with a measured (lysimeter) evapotranspiration of 0.133 g/cm².

It is difficult to draw any firm conclusions from these observed changes since an assumption that the changes are the result of vertical transport only is hardly justified. Although it has been stated that advection above the 900-mb level was negligible there does appear to have been some advective change affecting water-vapour content nearer the surface.

Several double-theodolite wind measurements were available for the day but only one balloon penetrated the inversion, earlier attempts being limited by stratus cloud. Wind changes with height suggest the presence of an inversion base near 76 mb which agrees well with the observed base near 77 mb above ground level.

The rate equation was applied to the data (in the same way as described in the section for 24 August), although its use on this occasion when changes of state occurred is questionable. The results were as follows:

Period GMT	Predicted rise millibars	Measured rise
0833–0933	4	9
0933–1151	17	12
1151–1321	8	37

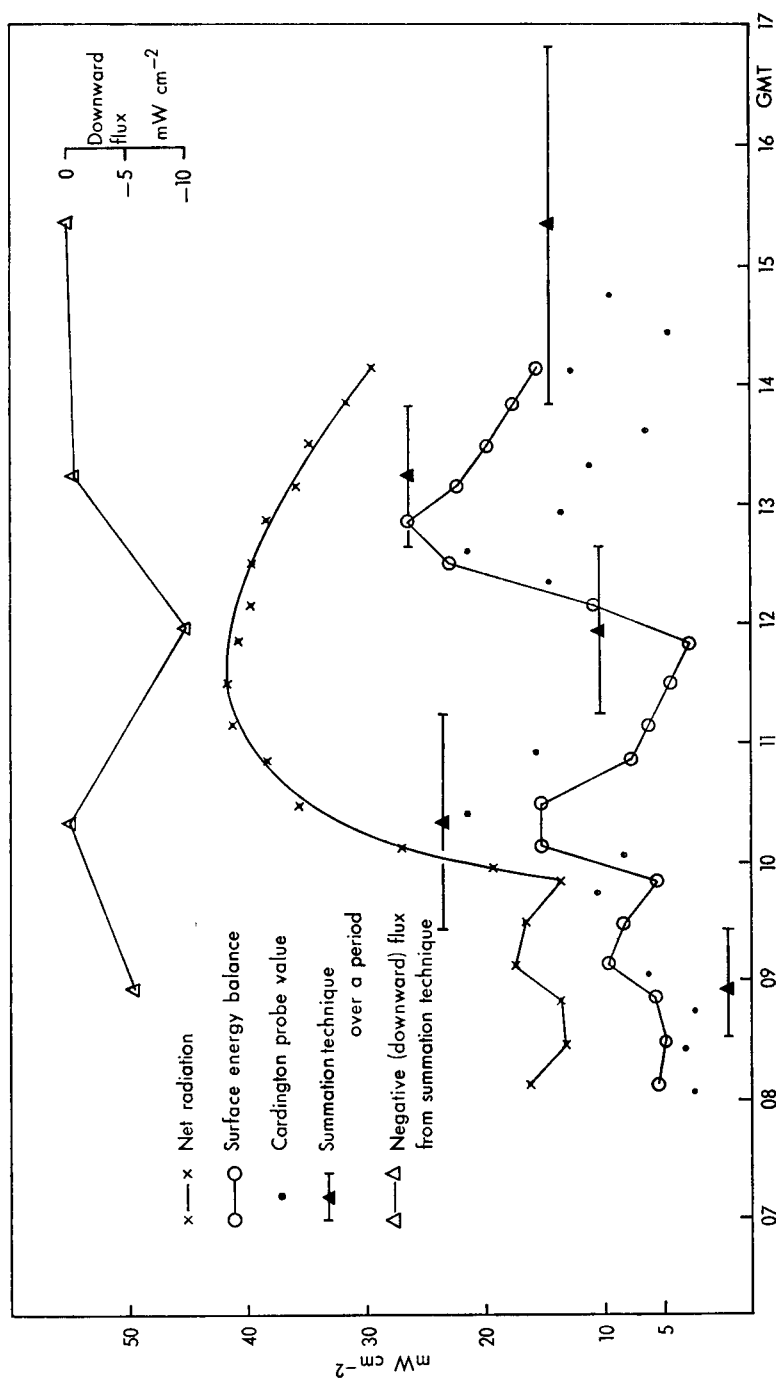


FIGURE 4—NET RADIATION AND SENSIBLE-HEAT FLUX IN MILLIWATTS/SQUARE CENTIMETRE ON 7 SEPTEMBER 1973

It may be noted that the final observed base height (at 1321 GMT) referred to the height of the higher 'synoptic' inversion, the lower inversion having been completely eroded during this latter period. Thus only the first two periods may be regarded as a test of the application of the equation, and it is of interest to note the agreement between the measured and predicted rise of the inversion, i.e. a rise of 21 mb, over the whole period 0833 to 1151 GMT. Comparing the fluctuations in surface sensible-heat flux and downward heat flux (Figure 4) it is difficult to draw firm conclusions regarding the actual ratios of the two fluxes over the period. The predicted rates of inversion rise (tabulated above) result from a straightforward application of the equation which assumes no entrainment.

12 September. An anticyclone over the Hebrides maintained a light easterly or south-easterly airflow over central and southern England. Near-cloudless conditions persisted at Cardington throughout the day; small amounts of high cloud were observed at times with one report, at 1000 GMT, of 1 okta of shallow cumulus, base 600 m. The only suspected advective change was that of increased moisture content near the surface during the late afternoon.

Shown in Figure 5 is the sequence of potential-temperature profiles based on three soundings from the surface to near the main capping inversion and one sounding restricted to the layer above about 100 mb (above ground level). The absence of a 'complete' sounding from the surface upwards between 0710 and 1135 GMT rules out any consideration of the lifting and erosion of a lower induced inversion which must have occurred. Thus the $W\theta$ summation is limited to the two periods between soundings (see Figure 5 inset).

The net-radiation curve and values of sensible-heat flux are shown in Figure 6 and show a reasonably smooth change with time, the two surface $W\theta$ summation values of heat flux agreeing well with the energy balance results.

Conclusions. The case of 24 August is an example of the complete 'warming out' of a nocturnal inversion finally resulting in dry adiabatic conditions within the boundary layer below the main inversion. The lower inversion warmed out 'passively' with no detected entrained heat flux. On 12 September similar 'warming out' of a lower inversion must have occurred beneath a clearly defined overhead capping inversion which was not affected by the changes in heat flux below. In each of these cases a reasonable sequence of radiative and sensible-heat flux changes is shown and the summation technique whereby sensible-heat flux may be derived from a series of temperature profiles is seen to be quite reliable.

The case of 7 September, although basically that of erosion of a low-level inversion beneath a higher capping inversion, is made more complex by the presence of the stratus cloud layer during the morning, by evaporative and condensation processes and by probable advective changes. The simple techniques described in this paper do not allow for such changes adequately.

The problem of advective and subsidence changes (or instrumental error) is difficult to resolve although the simple technique applied in the case of 24 August results in acceptable values of heat flux. The synoptic-scale techniques used to produce estimates of advection, e.g. wind shear in the vertical, cannot easily be applied to the relatively small changes within the boundary layer which may appreciably affect heat-flux estimates and water-budget calculations. Energy-balance estimates of sensible heat (the technique of residuals) depend largely on reliable evapotranspiration values. The data for

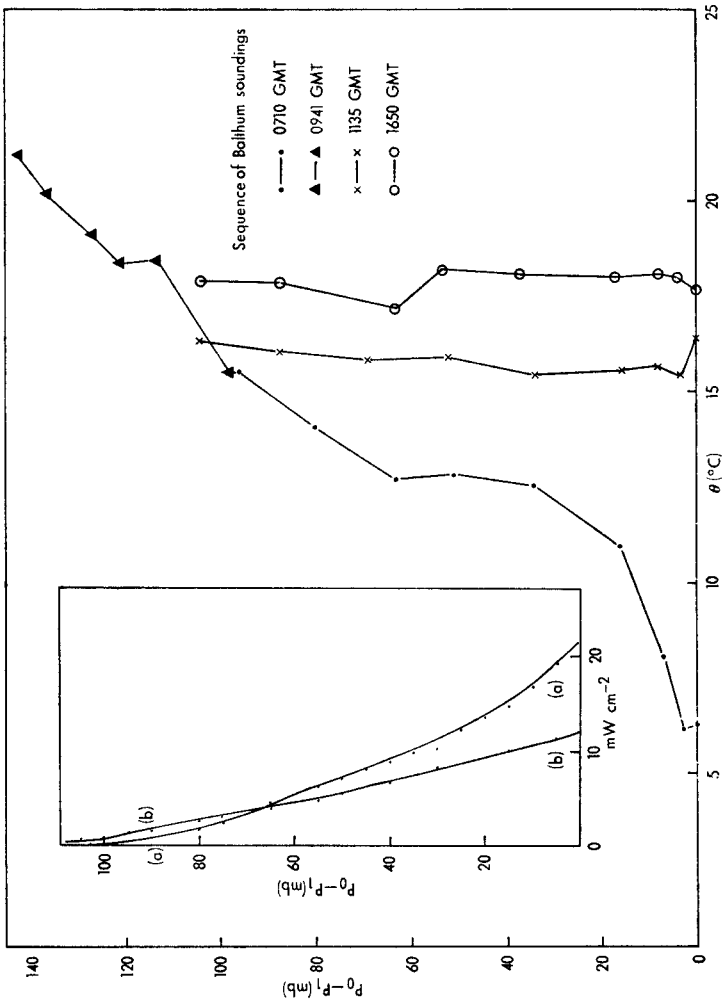


FIGURE 5—PROFILES OF POTENTIAL TEMPERATURE, θ , ON 12 SEPTEMBER 1973. $P_0 - P_1$ is height above surface in millibars. Inset shows upward sensible-heat flux in milliwatts/square centimetre. Summation values for periods between successive soundings, (a) 0710-1135 GMT and (b) 1135-1650 GMT.

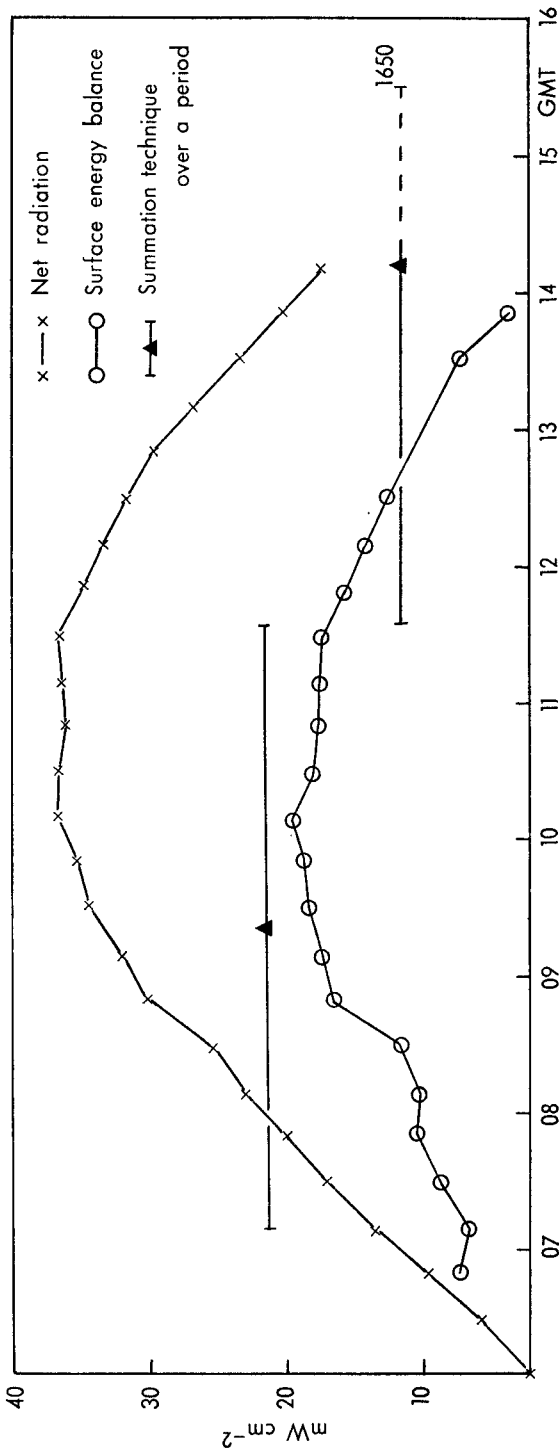


FIGURE 6—NET RADIATION AND SENSIBLE-HEAT FLUX IN MILLIWATTS/SQUARE CENTIMETRE ON 12 SEPTEMBER 1973

7 September suggest that these values are suspect if quoted for short periods when evapotranspiration is taking place at a high rate. Some difficulty was encountered regarding the reliability of soil-flux values: extrapolation of the 4-cm and 8-cm readings in order to arrive at a 'surface' value resulted in some high values. This may have been due to instrumental error. Values of sensible heat derived (using these values) were correspondingly very low. For the purpose of this analysis, the 8-cm reading was regarded as a 'surface' value. The measure of agreement between the surface-layer heat-flux values obtained by the three methods described is encouraging and could be important in planning further boundary-layer studies.

This is regarded as a 'pilot study' providing some useful guidance for the analysis of the more extensive radiosonde data which have resulted from experiment CABLE 74 (the Collaborative Atmospheric Boundary Layer Experiment) which involved Meteorological Research Unit, Cardington, Reading University (Department of Geophysics), Imperial College (Department of Physics), Meteorological Research Unit, Malvern, Chilbolton Radar and the radiosonde stations at Larkhill and Shoeburyness.

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AN INVESTIGATION INTO SPELLS OF WET AND DRY DAYS BY REGION AND SEASON FOR GREAT BRITAIN

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Summary. Distribution of wet and dry spells are considered in relation to Markov, simple logarithmic, modified logarithmic, and modified geometric models explained in this paper. Data from eight stations distributed over the British Isles show that a simple logarithmic model can usually describe dry-spell data while the modified logarithmic and geometric models describe wet-spell data. The variations in model parameters do not correlate well with region. Data considered by season for Oxford show that, on average, autumn and winter dry spells there are shorter than dry spells in spring and summer, while winter wet spells are slightly longer than those in the other seasons; these variations determine the model parameters.

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Introduction. Many investigations have been conducted into the distributions of sequences of wet and dry days. The most popular model used to fit the distributions of spell lengths has been the simple Markov model which assumes that the probability of any particular day being wet or dry depends only on the character of the previous day (for instance Chatfield,¹ Gabriel and Neumann²). Williams³ first suggested a logarithmic series as a fit to sequences of wet and dry days and this model has since been applied to other data (Cooke,⁴ Chatfield¹). Green⁵ proposed a modified logarithmic model of which the simple logarithmic and Markov models are special cases. This model, which used two parameters, satisfactorily fitted 33 out of 36 cases collected by Green and others; these included observations of duration of rainstorms, and of intervals between them, collected by Weiss.⁶ Yap⁷ proposed a modification to the simple Markov model in which the probability parameter (of a wet or dry day being followed by a similar day) was a variable, though a constant within any given spell length.

New data are here investigated in relation to seasonal and regional variations. Distributions from eight stations are compared. Those for Oxford are further divided into four seasons and examined in more detail.

The models. The probabilities of spells of length 1, 2, 3 . . . r wet or dry days are defined by the various models as follows:

Model 1: Markov Chain Model

q, q^2, \dots, q^r , with normalizing constant $\frac{1-q}{q}$.

Model 2: Williams's logarithmic model

$q, q^2/2, q^3/3, \dots, q^r/r$, with normalizing constant $\frac{1}{\log(1-q)}$.

Model 3: Green's modified logarithmic model

$\frac{q}{1+a}, \frac{q^2}{2+a}, \dots, \frac{q^r}{r+a}$ with $0 \leq a \leq \infty$ and the normalizing constant

determined by the requirement $\sum_r \frac{q^r}{r+a} = 1$. In each case the

normalizing constant ensures that the total probability is unity. In order to fit models 1 and 2 from data the mean spell length is used (i.e. the total number of wet (or dry) days divided by the total number of wet (or dry) spells) to find q .

For model 1, mean spell length = $\sum_r \frac{1-q}{q} q^r r = \frac{1}{1-q}$.

For model 2, mean spell length = $\sum_r \frac{-1}{\log(1-q)} \frac{r q^r}{r} = \frac{-q}{\log(1-q)(1-q)}$.

For model 1, q can be found directly from the mean spell length; for model 2 it is found by a recursive process or from tables published by Williamson and Bretherton.⁸

It may be noticed that models 1 and 2 are special cases of model 3 for $a = \infty$ and 0 respectively.

To fit model 3 the method of minimum chi-square is used. We let q approach 0 from 1 and let a approach 0 from some value greater than, say, 6 in successive steps; the distribution for given a, q is tested for fit at each step by the chi-square test. The parameters a and q are altered each time the chi-square value falls as compared with the values of a, q for previous smallest values of chi-square. In applying the chi-square tests, spells of length greater than a certain value (about 15) are grouped together into one category. The program stops when chi-square falls below a certain value determined by the number of categories; the a and q values for the minimum chi-square value are taken as best fit values.

For model 4 we assume that the probability of a dry or wet spell is p , where p is a random variable having a constant value within any one run, but different values in different runs (as Yap⁷); p is assumed to be a random variate

$$f(p) = \frac{p^{a-1} (1-p)^{b-1}}{B(a, b)}$$

where a, b are constants of the distribution and $B(a, b)$ is the Beta function.

The probability of a run of days is given by

$$P(r) = \frac{1}{B(a, b)} \int_0^1 (1-p) p^{r-1} (1-p)^{b-1} p^{a-1} dp,$$

where $(1-p)$ is a normalizing factor and p^{r-1} arises from $r-1$ days following the first wet (or dry) day. Then

$$P(r) = \frac{B(a+r-1, b+1)}{B(a, b)},$$

$$P(1) = \frac{b}{a+b}, \text{ and } r \geq 2,$$

$$P(r) = \frac{a+r-2}{a+b+r-1} P(r-1),$$

where we have used the definitions

$$B(x, y) = \frac{(x-1)! (y-1)!}{(x+y-1)!} = \int_0^1 p^{x-1} (1-p)^{y-1} dp.$$

To fit the model we take factorial moments about the origin U'_1, U'_2 for the first two moments, i.e.

$$\begin{aligned} U'_1 &= \int_0^1 f(p) (1-p) \sum_0^\infty p^{r-1} r dp \\ &= \frac{1}{B(a, b)} \int_0^1 \frac{1}{(1-p)^2} (1-p) p^{a-1} (1-p)^{b-1} dp \\ &= \frac{B(a, b+1)}{B(a, b)} = \frac{a+b-1}{b-1} \end{aligned}$$

$$\begin{aligned}
 U_2 &= \int_0^1 f(p) (1-p) \sum_{r=0}^{\infty} p^{r-1} r(r-1) dp \\
 &= \frac{1}{B(a, b)} \int_0^1 p^{a-1} (1-p)^{b-1} \frac{2p}{(1-p)^2} dp, \\
 &= \frac{2}{B(a, b)} B(a+1, b-2), \\
 &= \frac{2a(a+b-1)}{(b-1)(b-2)}.
 \end{aligned}$$

$$\text{Then } b = \frac{2U'_1(U'_1-1) - 2U'_2}{2U'_1(U'_1-1)U'_2},$$

$$a = (U'_1-1)(b-1).$$

U'_1 is equated to mean spell length and U'_2 to the difference between mean-square spell length and mean spell length.

Persistence. As a measure of persistence we may use the ratio of the probability of spell length $(r+1)$ to spell length, r , $F(r)$ say. For models 1, 2 and 3, $F(r) = P(r+1)/P(r) = q((r+a)/(r+a+1))$. For the general case of model 3, $0 \leq a \leq \infty$; models 1 and 2 are special cases of model 3 for $a = \infty$ and 0 respectively. $F(r)$ is constant for model 1 for all r and equals q . In general, $F(r)$ increases with spell length r and with model parameter a ; its rate of increase decreases as r increases and $F(r)$ tends to q in the limit.

For model 4, $F(r) = P(r+1)/P(r) = (a+r-3)/(a+b+r-1)$ and the measure of persistence increases with spell length, tending to 1 for large r .

Model fitting for eight stations. The data used were for 40-year periods: 1921-60 for York, Cwm Dyli (North Wales), Oxford, Falmouth, March and Edgbaston, 1931-70 for Edinburgh; for Whitby, the shorter period 1921-42 was used. Difficulty was experienced in finding stations with long-term continuous rainfall records with a constant threshold for recording rainfall; threshold values were 0.01 in for all stations apart from Edinburgh and Edgbaston with 0.2 mm. These data are given in Appendix I (dry spells), Appendix II (wet spells); graphs of spell length distribution for Edinburgh, Falmouth, Cwm Dyli and March are illustrated as representative examples in Figures 1 to 6.

The chi-square test was used to test the fit of models 1 to 4 to the observed distribution with an acceptance level of $P(\chi^2) \geq 0.05$. For dry spells the logarithmic model fitted the data for all stations except March and Edgbaston. For March the modified logarithmic model fitted the data for small a ($a = 0$ for the simple logarithmic model); for Edgbaston no model fitted the dry-spell data. Neither the Markov nor the modified geometric models produced distributions to fit any of the dry-spell data. The parameter q did not show any systematic variation among the stations.

For wet spells the modified geometric and modified logarithmic models fitted most data. The exceptions were Cwm Dyli for the geometric model,

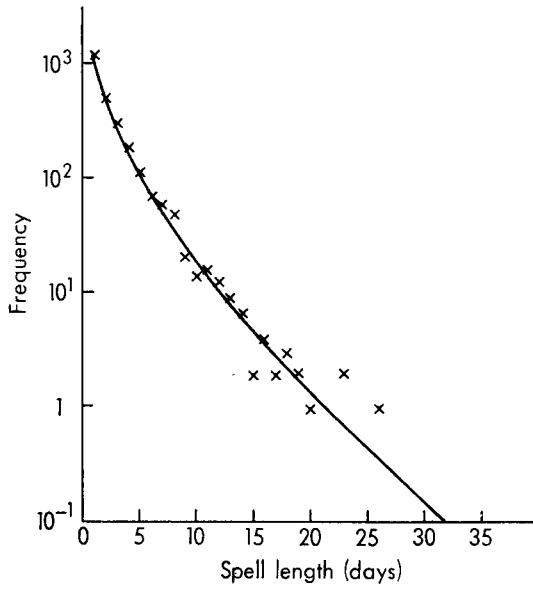


FIGURE 1—DRY SPELLS AT EDINBURGH, LOGARITHMIC MODEL
 $q = 0.82$.

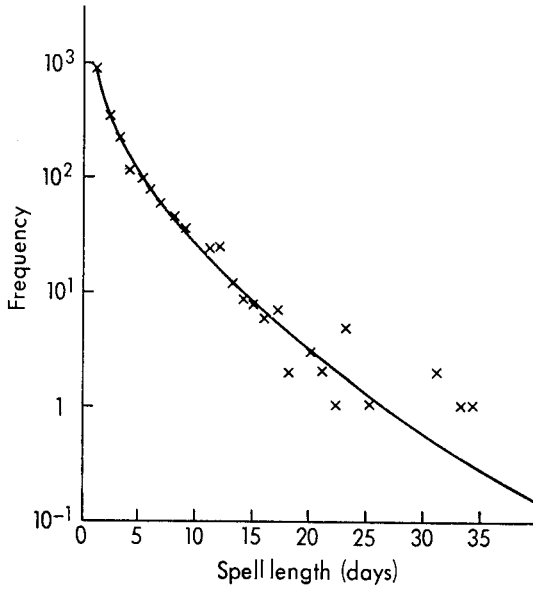


FIGURE 2—DRY SPELLS AT FALMOUTH, LOGARITHMIC MODEL
 $q = 0.87$.

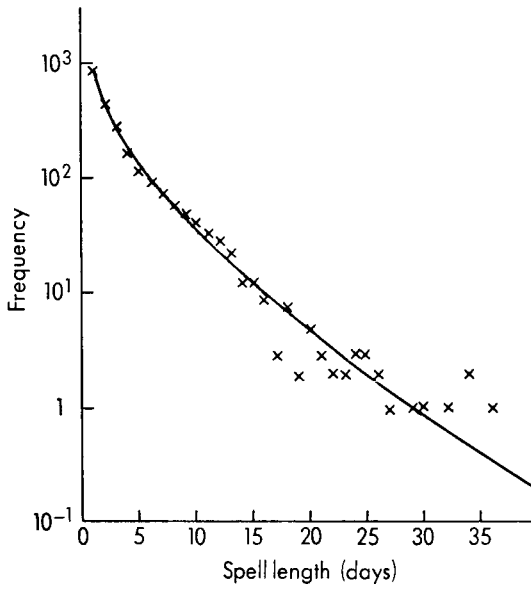


FIGURE 3—DRY SPELLS AT MARCH, MODIFIED LOGARITHMIC MODEL
 $q = 0.87$, $a = 0.34$.

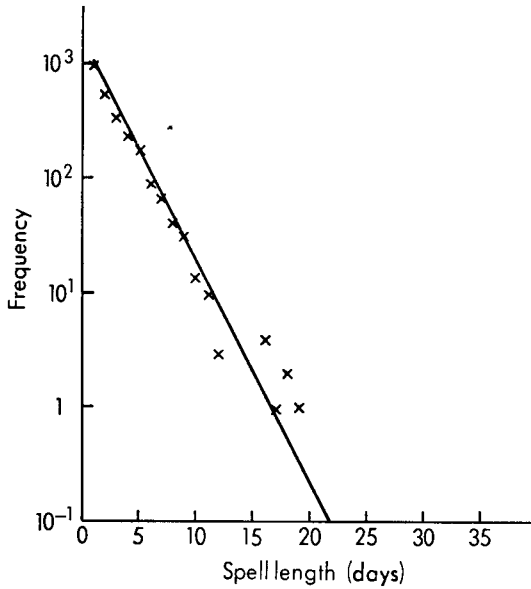


FIGURE 4—WET SPELLS AT EDINBURGH, MARKOV MODEL
 $q = 0.64$.

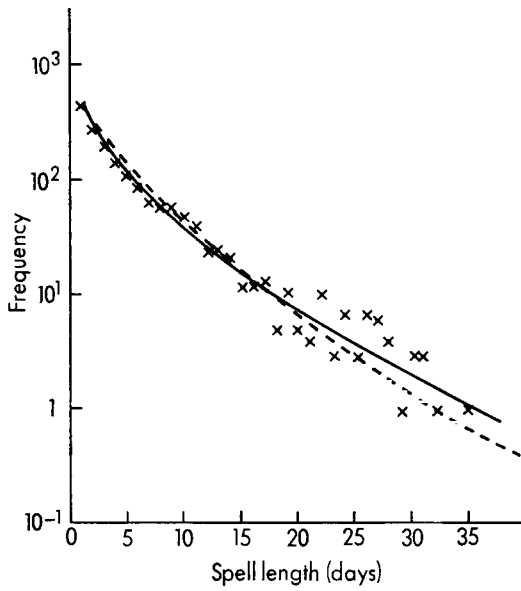


FIGURE 5—WET SPELLS AT CWM DYLI
 — modified logarithmic model, $q = 0.90$, $a = 1.18$.
 - - - modified geometric model.

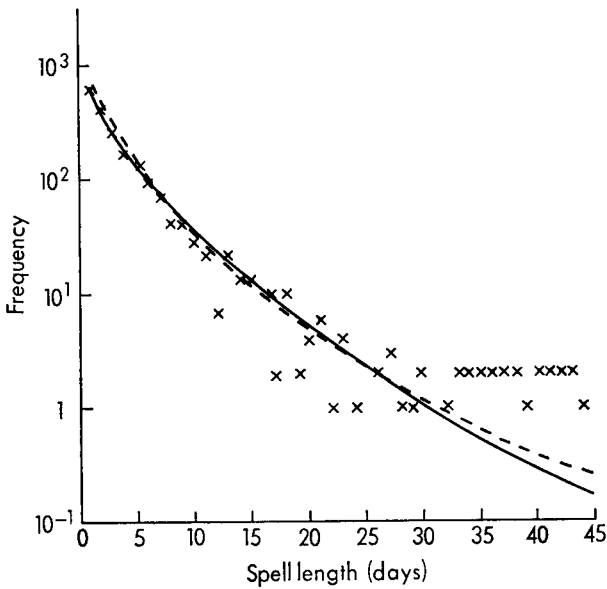


FIGURE 6—WET SPELLS AT FALMOUTH
 — modified logarithmic model, $q = 0.88$, $a = 0.92$.
 - - - modified geometric model.

Falmouth for the modified logarithmic model and Edinburgh fitted by neither modified model. However, a simple Markov model, which is a special case of both modified models, fitted the Edinburgh data. The modified logarithmic model usually produced a slightly better fit than the modified geometric model, though differences were only apparent for longer, less-frequent spells.

Variations of the parameters a and q for wet spells did not correlate well with region or with mean annual rainfall. Cwm Dyli (mean annual rainfall 140.46 in (3567.68 mm) for the period 1916–50) and Falmouth (43.00 in, 1092.20 mm), the two wettest stations, had slightly higher values of q than the other stations and showed slightly greater persistence of wet spells. The other stations had mean annual rainfall in decreasing order as follows: Edgbaston 30.70 in (779.78 mm), Edinburgh 27.53 in (699.26 mm), Whitby 25.66 in (651.76 mm), York 24.70 in (627.38 mm), and March 23.07 in (585.98 mm).

An examination was made of the effect of a change of threshold for the two stations which recorded in millimetres. It was found that with a threshold value of 0.1 mm the Edgbaston dry-spell data fitted a logarithmic model (no fit found for 0.2 mm), and that Edinburgh wet-spell data fitted both modified models (a Markov fit found for 0.2 mm). For Edgbaston wet-spell data and for Edinburgh dry-spell data the change of threshold was found to cause only a slight change in the model parameters.

Comparative persistence of wet and dry spells. Using models 1 to 3 the values of the measure of persistence $F(r)$ were compared for wet and dry spells for each station. For March, $F(r)$ was larger for all dry spells than for wet spells. For Edinburgh, York, Edgbaston and Oxford, $F(r)$ was larger for dry spells of length greater than two days; for Whitby, $F(r)$ was larger for dry spells longer than five days. For Edinburgh, where a Markov model produced a best fit to wet-spell data, $F(r)$ was of course constant. For the wetter stations, Cwm Dyli and Falmouth, $F(r)$ was larger for wet spells for all r . Thus we infer that dry spells are more persistent at 'dry' stations and wet spells are more persistent at 'wet' stations. For intermediate stations wet spells are more persistent for short spells only. The variations probably reflect the passage of synoptic features. Anticyclones tend to build up slowly over two or three days and last for longer periods than do individual depressions. For 'wet' stations effects of minor disturbances are greater than at other stations and wet spells tend to be more persistent than dry spells. However, analysis of spell data does not distinguish the effect of individual disturbances; a long wet spell may result from several successive depressions.

Seasonal variations (see Appendices III and IV and Figures 7–9). The Oxford data for 1852–1970 were divided into four seasons—winter (December to February), spring (March to May), summer (June to August) and autumn (September to November), the divisions between seasons being taken at the end of a spell. Each seasonal set of data was tested for the distribution of spells according to the above model. Dry spells again fitted the log model and wet spells the modified geometric model. For dry spells the mean spell lengths were similar for autumn and winter (2.875 and 2.921 days) and for spring and summer (3.498 and 3.344); the corresponding values of the parameters q in the logarithmic model were 0.84 for autumn and winter, 0.88 for spring and 0.87 for summer. For wet spells it was found that mean spell lengths

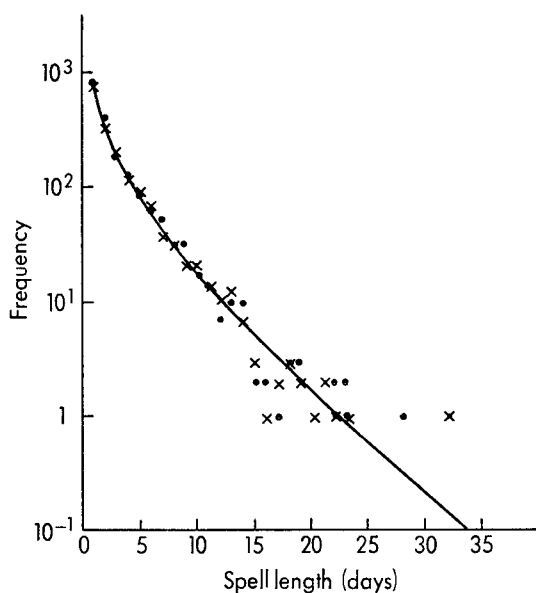


FIGURE 7—DRY SPELLS AT OXFORD, LOGARITHMIC MODEL

● Autumn × Winter

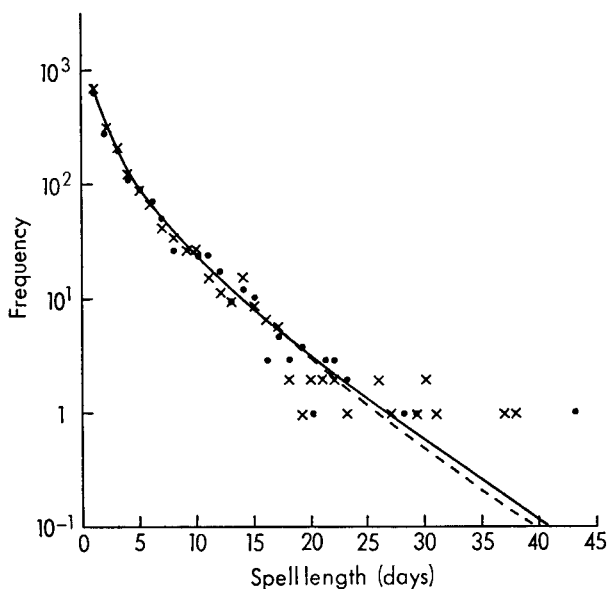


FIGURE 8—DRY SPELLS AT OXFORD, LOGARITHMIC MODEL

Continuous line and dots refer to spring; $q = 0.88$.

Pecked line and crosses refer to summer; $q = 0.87$.

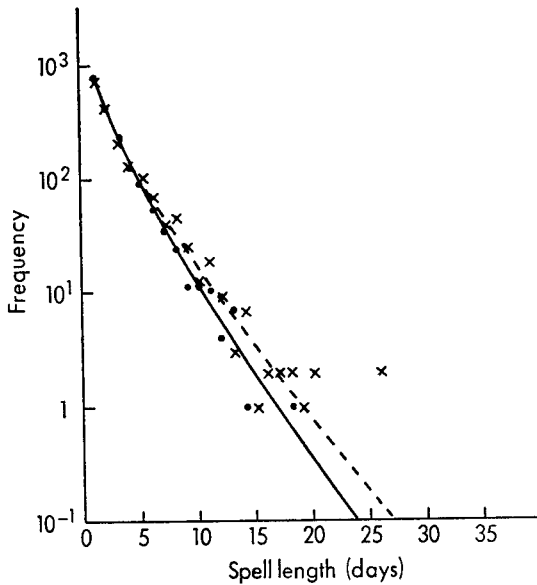


FIGURE 9—WET SPELLS AT OXFORD, MODIFIED LOGARITHMIC MODEL
Continuous line and dots refer to summer; $q = 0.87$, $a = 1.09$.
Pecked line and crosses refer to winter; $q = 0.78$, $a = 1.59$.

decreased from winter (2.932) to summer (2.621) with spring (2.783) and autumn (2.750) having similar lengths. The parameters a and q which produced the best fit to spring and autumn wet spells also produced a good (but not best) fit to summer wet spells (see table below).

	a	q	$P(\chi^2)$
Spring	2.075	0.75	0.50
Autumn	2.075	0.75	0.05
Summer	2.075	0.75	0.05
	1.087	0.75	0.30
Winter	1.581	0.78	0.10

Cumulative distributions. As regards extremes, a model which describes cumulative spell distributions, i.e. the number of spells of length greater than a specified value, may be of more practical value than one describing individual spells. For this reason the spell data were also considered cumulatively. For dry spells only the modified logarithmic model was found to fit the cumulative data and that at only four out of the eight stations; the parameters a and q of the model were 0.87 and 1.09 respectively for York and Oxford, 0.81 and 2.07 for Cwm Dyli, and 0.87 and 2.07 for March. On the other hand it was found that none of the models fitted cumulative wet-spell data. It was usually the rarer long spells which failed to fit the models for cumulative data since after the summation of data their relative weight in the fit was decreased.

Conclusions. We may agree with Green's conclusion that the modified logarithmic model (of which Markov's model and the simple logarithmic model are special cases) fits most spell data. As a first approximation, we may say that the simple logarithmic model fits dry-spell data with q about 0.85; for wet spells, the modified logarithmic model fits most data, with a about 2 or 3 and q about 0.7 or 0.8 for other stations. The modified geometric model also fits most wet-spell data. The models give only a rough guide to the occurrence of infrequent long spells.

Seasonally, dry spells are slightly longer for spring and summer than for autumn and winter, one q -value for each half of the year being sufficient to describe the data. For wet spells, different values of a and q are needed for longer winter spells than those for other seasons.

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APPENDIX I—DRY-SPELL FREQUENCIES

Spell length days	Edinburgh		York		Whitby		Cwm Dyli		Oxford		Falmouth		March		Edgbaston		Edgbaston*	
	Observed	Log. model	Observed	Log. model	Observed	Log. model	Observed	Log. model	Observed	Log. model	Observed	Log. model	Observed	Log. model	Observed	Log. model	Observed	Log. model
1	1241	1280.9	1004	1033.4	662	689.3	886	862.6	1004	1034.8	904	868.9	944	951.0	1039	1068.1	1045	1076.9
2	524	524.7	475	444.4	287	276.8	340	359.3	476	444.5	358	377.9	487	476.7	460	456.9	459	454.0
3	311	286.6	228	254.8	154	148.2	170	199.6	261	254.5	216	219.2	319	291.7	269	260.7	269	255.2
4	194	176.1	197	164.4	92	80.3	120	124.7	141	164.0	116	143.0	179	196.4	154	167.3	135	161.4
5	120	115.4	107	113.1	57	57.4	84	83.1	131	112.7	92	99.5	138	139.6	141	114.5	142	108.9
6	74	78.8	82	81.1	51	58.4	65	57.7	99	80.7	73	72.1	164	102.9	81	81.6	81	76.5
7	61	55.4	60	59.8	32	26.4	59	41.2	46	59.4	53	53.8	70	78.0	73	59.9	63	55.3
8	50	39.7	40	45.0	19	18.6	36	30.0	38	44.6	47	40.9	61	59.9	39	44.8	36	40.8
9	21	28.9	43	34.4	9	13.3	26	22.3	39	34.1	36	34.6	52	46.8	43	34.1	37	30.6
10	15	21.3	31	26.6	13	9.6	17	16.7	26	26.4	29	24.8	43	37.0	34	26.3	27	23.2
11	17	15.9	24	20.8	7	7.0	17	12.6	22	20.6	24	19.6	36	29.5	23	26.4	17	17.8
12	14	11.9	19	16.4	4	5.2	11	9.7	15	16.2	25	15.6	30	23.7	18	16.0	13	13.7
13	9	9.0	11	13.0	3	3.8	6	7.4	9	12.9	12	12.5	24	19.2	10	12.7	9	10.7
14	7	6.9	10	10.4	0	2.8	3	5.7	15	10.3	9	10.1	13	15.6	8	10.1	5	8.4
15	2	5.2	5	8.4	0	2.1	3	4.5	7	8.2	8	8.2	13	12.8	10	6.6	8	6.6
16	4	4.0	4	6.7	1	1.6	3	3.5	4	6.6	6	6.7	9	10.5	8	6.4	7	5.2
17	2	3.1	5	5.5	1	1.2	2	2.7	3	5.4	7	5.5	3	8.7	1	5.2	3	4.1
18	3	2.4	2	4.4	1	0.9	1	2.2	3	4.3	2	4.5	8	7.2	2	4.2	2	3.3
19	2	1.9	4	3.6	0	0.7	1	1.7	4	3.5	4	3.7	2	5.9	3	3.4	1	2.6
20	1	1.5	4	2.9	1	0.5	1	1.3	1	2.9	3	3.1	5	4.9	2	2.8	2	2.1
21	0	1.1	1	2.4	0	0.4	0	1.1	2	2.4	2	2.5	3	4.1	0	2.3	0	1.7
22	0	0.9	1	2.0	0	0.3	0	0.8	3	1.9	1	1.4	2	3.4	3	1.8	2	1.4
23	2	0.7	1	1.6	1	0.2	1	0.7	1	1.6	5	1.8	2	2.9	0	1.5	0	1.1
24	0	0.5	0	1.3	0	0.1	1	0.5	0	1.3	0	1.5	3	2.4	0	1.2	0	0.9
25	0	0.4	1	1.1	0	0.1	0	0.4	1	1.1	1	1.2	3	2.0	0	1.0	0	0.7
26	1	0.3	2	0.9	0	0.1	0	0.3	1	0.9	0	1.0	2	1.7	0	0.8	0	0.6
27	0	0.3	0	0.8	0	0.1	0	0.3	0	0.7	0	0.9	1	1.4	0	0.7	0	0.5
28	0	0.2	0	0.6	0	0.1	0	0.2	2	0.6	0	0.7	0	1.2	0	0.6	0	0.4
29	0	0.2	1	0.5	0	0.1	1	0.2	1	0.5	0	0.6	1	1.0	0	0.5	0	0.3
30	0	0.1	0	0.4	0	0.0	0	0.1	1	0.4	0	0.5	1	0.9	1	0.4	0	0.3
31	0	0.1	1	0.4	0	0.0	0	0.1	1	0.3	2	0.4	0	0.7	0	0.3	0	0.2
32	0	0.1	1	0.3	0	0.1	0	0.1	0	0.3	0	0.4	1	0.6	1	0.2	1	0.2
33	0	0.1	0	0.3	0	0.0	0	0.0	0	0.2	1	0.3	0	0.5	0	0.2	0	0.1
34	0	0.1	2	0.2	0	0.0	0	0.0	0	0.2	0	0.3	2	0.4	1	0.2	1	0.1
35	0	0.2	0	0.2	0	0.0	0	0.0	0	0.2	0	0.2	0	0.4	0	0.1	0	0.1
36	0	0.2	0	0.2	0	0.0	0	0.0	0	0.1	0	0.2	1	0.3	0	0.1	0	0.1
37	0	0.2	0	0.2	0	0.0	1	0.1	1	0.1	0	0.1	0	0.2	0	0.1	0	0.1
38	0	0.2	0	0.2	0	0.0	0	0.0	0	0.1	0	0.1	0	0.2	0	0.1	0	0.1
39	0	0.2	0	0.2	0	0.0	0	0.0	0	0.1	0	0.1	0	0.2	0	0.1	0	0.1
40	0	0.1	0	0.1	0	0.0	0	0.0	0	0.1	0	0.1	0	0.2	0	0.1	0	0.1
χ^2_a	15.7	20.0	13.3	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.1	20.1	18.7	18.7	31.5	27.9	27.9	27.9
$P(\chi^2_a)$	0.40	0.30	0.30	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.30	0.30	0.40	0.40	0.05	0.05	0.05	0.05
q	0.82	0.86	0.863	0.833	0.833	0.833	0.833	0.833	0.833	0.833	0.870	0.870	0.875	0.875	0.85	0.85	0.84	0.84

Observed denotes observed frequency; Log. denotes expected frequency (logarithmic model).
 * When threshold decreased from 0.2 mm to 0.1 mm.

APPENDIX II—WET-SPELL FREQUENCIES

Spell length	Edinburgh		Observed	York	Modi-	Observed	Whitby	Modi-	Observed	Cwm Dyl	Modi-
	Observed	Expected	Observed	Modi-	Modi-	Observed	Modi-	Modi-	Observed	Modi-	Modi-
		fre-		fied	fied		fied	fied		fied	fied
		quency		log.	geo-		log.	geo-		log.	geo-
		(Markov)			metric			metric			metric
<i>days</i>											
1	1003	950.8	907	895.5	882.9	523	489.4	492.8	477	495.6	413.9
2	570	612.7	520	504.2	531.2	293	302.6	309.1	322	308.6	313.2
3	336	394.9	305	307.9	327.9	182	193.7	197.3	212	213.2	239.2
4	251	254.4	204	197.5	207.2	121	127.0	127.9	153	156.3	184.2
5	195	164.0	136	130.8	133.7	74	84.8	84.2	127	119.0	143.0
6	96	105.7	92	88.7	87.9	62	57.4	56.2	95	93.0	111.9
7	68	68.1	64	61.2	58.8	40	39.4	38.0	68	74.1	88.1
8	43	43.9	41	42.8	40.0	39	27.2	26.0	63	60.0	69.9
9	33	28.3	25	30.3	27.6	12	19.0	18.0	62	49.1	55.7
10	14	18.2	26	21.6	19.3	11	13.3	12.6	51	40.6	44.7
11	10	11.7	11	15.6	13.7	13	9.3	8.9	41	33.9	36.1
12	3	7.6	9	11.3	9.8	7	6.6	6.4	25	28.4	29.3
13	11	4.9	2	8.2	7.1	4	4.7	4.6	26	24.0	23.9
14	3	3.1	6	6.0	5.2	4	3.4	3.3	24	20.4	19.6
15	0	2.0	6	4.4	3.9	1	2.4	2.4	12	17.3	16.1
16	4	1.3	2	3.2	2.9	3	1.7	1.8	13	14.8	13.3
17	1	0.8	2	2.4	2.2	3	1.3	1.3	14	12.7	11.1
18	2	0.5	4	1.8	1.6	1	0.9	1.0	5	11.0	9.2
19	1	0.3	3	1.3	1.3	1	0.7	0.8	11	9.5	7.7
20	0	0.2	0	1.0	1.0	1	0.5	0.6	5	8.2	6.5
21	0	0.1	0	0.7	0.7	0	0.3	0.4	4	7.1	5.4
22	0	0.1	1	0.6	0.6	0	0.2	0.3	11	6.2	4.6
23	0	0.1	0	0.4	0.5				3	5.4	3.9
24	0	0.0	0	0.3	0.3				7	4.7	3.7
25	0	0.0	1	0.2	0.2				3	4.1	2.8
26	0	0.0	1	0.2	0.2				7	3.6	2.5
27	1	0.0							6	3.1	2.1
28									4	2.8	1.8
29									1	2.4	1.6
30									3	2.1	1.4
31									3	1.9	1.2
32									1	1.6	1.0
33									0	1.4	0.9
34									0	1.3	0.8
35									1	1.1	0.7
36									0	1.0	0.6
37											
38											
39											
40											
41											
42											
43											
44											
χ^2		22.2		10.4	12.0		14.8	16.8		24.7	49.4
$P(\chi^2)$		0.05		0.30			0.20			0.30	0.001
q		0.64		0.78			0.76			0.90	
a				1.58			3.43			1.18	

APPENDIX II *continued*

Observed	Oxford Modi- fied log.	Modi- fied geo- metric	Observed	Falmouth Modi- fied log.	Modi- fied geo- metric	Observed	March Modi- fied log.	Modi- fied geo- metric	Observed	Edgbaston Modi- fied log.	Modi- fied geo- metric
884	873.1	865.0	628	660.8	628.9	1328	1270.3	1294.3	884	902.0	871.2
532	525.2	528.6	427	362.7	409.5	577	584.6	615.3	554	519.5	538.9
310	328.8	330.1	264	251.1	276.5	283	295.4	304.6	311	321.4	338.2
197	211.6	210.3	164	176.2	192.4	176	157.6	156.3	219	207.9	217.2
131	139.0	138.6	137	129.0	137.4	83	87.1	82.9	154	138.5	142.1
96	92.7	89.0	98	97.2	100.3	58	49.4	45.3	90	94.4	94.5
55	62.6	60.3	68	74.8	74.7	19	28.5	25.4	59	65.4	63.8
50	42.7	41.0	43	58.5	56.6	10	16.7	14.6	48	45.8	43.8
39	29.4	28.2	41	46.3	43.6	13	9.9	8.6	32	32.5	30.4
14	20.3	19.7	28	37.1	34.0	6	5.9	5.1	25	23.2	21.4
14	14.2	13.9	22	29.9	27.0	4	3.6	3.1	14	16.7	15.2
11	9.9	9.9	7	24.3	21.5	1	2.2	2.0	11	12.1	10.9
9	7.0	7.1	22	19.9	17.3	2	1.3	1.2	9	8.8	7.9
6	4.9	5.2	13	16.3	14.1	0	0.8	0.8	6	6.5	5.8
2	3.5	3.8	13	13.5	11.6	0	0.5	0.5	4	4.7	4.3
1	2.5	2.8	10	11.2	9.6	1	0.3	0.3	5	3.5	3.2
1	1.8	2.1	2	9.3	8.0	0	0.2	0.2	3	2.6	2.4
3	1.3	1.6	10	7.8	6.8	0	0.1	0.1	2	1.9	1.8
2	0.9	1.2	2	6.5	5.7	0	0.1	0.1	1	1.4	1.4
1	0.7	0.9	4	5.4	4.8				0	1.1	1.1
1	0.5	0.7	6	4.6	4.1				1	0.8	0.8
0	0.3	0.5	1	3.9	3.5				0	0.6	0.6
1	0.2	0.4	4	3.2	3.0				1	0.4	0.5
0	0.2	0.3	1	2.7	2.6				0	0.3	0.4
			0	2.3	2.3				1	0.2	0.3
			2	2.0	2.0				0	0.2	0.2
			3	1.7	1.8				1	0.1	0.2
			1	1.4	1.6				0	0.1	0.2
			1	1.2	1.4						
			2	1.0	1.2						
			1	0.9	1.1						
			1	0.7	1.0						
			2	0.6	0.9						
			2	0.5	0.8						
			2	0.5	0.7						
			2	0.4	0.6						
			2	0.3	0.6						
			2	0.3	0.6						
			1	0.3	0.5						
			2	0.2	0.4						
			2	0.2	0.4						
			2	0.2	0.3						
			2	0.2	0.3						
			1	0.1	0.3						
11.2		12.7		50.2	21.5		14.1	1.61		4.7	5.6
0.60		0.40		0.01	0.20		0.10	0.05		0.98	0.98
0.75				0.88			0.66			0.78	
3.05				0.92			1.35			1.81	

APPENDIX III—SEASONAL DRY-SPELL FREQUENCIES, OXFORD

Spell length days	Winter		Spring		Summer		Autumn	
	Observed	Log. model	Observed	Log. model	Observed	Log. model	Observed	Log. model
1	831	828.5	685	713.5	758	769.3	827	869.3
2	331	349.9	301	314.7	327	336.1	408	365.6
3	205	197.1	204	185.0	207	195.8	191	205.0
4	119	124.9	118	122.4	130	128.3	131	129.3
5	94	84.4	98	86.4	97	89.7	87	87.0
6	70	59.4	76	63.5	71	65.3	62	61.0
7	38	43.0	54	48.0	44	48.9	54	44.0
8	33	31.8	28	37.0	37	37.4	32	32.3
9	21	23.9	31	29.0	29	29.0	34	24.2
10	22	18.2	26	23.1	28	22.8	18	18.3
11	14	13.9	27	18.5	16	18.1	15	14.0
12	10	10.8	19	14.9	12	14.5	7	10.8
13	13	8.4	10	12.2	10	11.7	10	8.4
14	6	6.6	13	10.0	16	9.5	10	6.5
15	3	5.2	11	8.8	9	7.8	2	5.1
16	1	4.1	3	6.8	7	6.3	2	4.0
17	2	3.3	5	5.6	5	5.2	1	3.2
18	3	2.6	3	4.7	2	4.3	3	2.5
19	2	2.1	4	3.9	1	3.6	3	2.0
20	1	1.7	1	3.3	2	3.0	1	1.6
21	2	1.4	3	2.8	2	2.5	0	1.3
22	1	1.1	3	2.3	2	2.1	1	1.0
23	2	0.9	2	2.0	1	1.7	1	0.8
24	1	0.7	0	1.7	0	1.4	0	0.7
25	1	0.6	0	1.4	0	1.2	0	0.5
26	0	0.5	0	1.2	2	1.0	0	0.4
27	0	0.4	0	1.0	1	0.9	0	0.4
28	0	0.3	1	0.9	0	0.7	1	0.3
29	0	0.2	1	0.7	1	0.6	0	0.2
30	0	0.2	0	0.6	2	0.5	0	0.2
31	0	0.1	1	0.5	1	0.4	0	0.2
32	1	0.1	0	0.5	0	0.4	0	0.1
33	0	0.1	0	0.4	0	0.3	0	0.1
34	0	0.1	0	0.3	0	0.3	0	0.1
35	0	0.1	0	0.3	0	0.2	0	0.1
χ^2		20.34		23.4		12.1		11.5
$P(\chi^2)$		0.70		0.15		0.70		0.10
q		0.84		0.88		0.87		0.84

APPENDIX IV—SEASONAL WET-SPELL FREQUENCIES, OXFORD

Spell length days	Winter			Spring			Summer			Autumn		
	Observed	Modified log.	geometric	Observed	Modified log.	geometric	Observed	Modified log.	geometric	Observed	Modified log.	geometric
1	718	697.1	680.4	680	682.3	660.9	757	816.7	734.3	762	746.6	744.8
2	409	392.6	408.9	393	386.0	392.3	404	414.2	424.9	434	422.5	435.9
3	212	239.7	252.2	211	232.4	238.5	245	234.6	251.9	241	254.5	262.0
4	142	153.7	159.8	144	145.6	148.2	150	141.4	151.9	174	159.4	161.4
5	105	101.9	103.3	90	93.8	94.0	98	88.6	93.5	84	102.7	101.7
6	69	69.1	68.2	61	61.6	60.7	56	57.1	58.6	68	67.5	65.3
7	40	47.7	45.8	44	41.1	39.8	38	37.5	37.3	46	45.0	42.8
8	46	33.4	31.3	39	27.8	26.6	26	25.0	24.2	21	30.4	28.5
9	26	23.6	21.7	23	19.0	18.0	12	16.9	15.8	28	20.8	19.3
10	13	16.9	15.3	13	13.0	12.3	12	11.5	10.5	11	14.3	13.2
11	19	12.1	10.9	4	9.0	8.6	11	7.9	7.1	13	9.9	9.2
12	9	8.8	7.9	7	6.3	6.0	4	5.5	4.8	5	6.9	6.5
13	3	6.4	5.7	3	4.4	4.3	7	3.8	3.3	10	4.8	4.6
14	7	4.7	4.2	3	3.1	3.0	1	2.7	2.3	3	3.4	3.3
15	1	3.4	3.1	1	2.2	2.2	0	1.9	1.6	1	2.4	2.4
16	2	2.5	2.4	0	1.6	1.6	2	1.3	1.2	2	1.7	1.8
17	2	1.9	1.8	1	1.1	1.2	2	0.9	0.8	0	1.2	1.3
18	2	1.4	1.4	2	0.8	0.9	1	0.7	0.6	2	0.9	1.0
19	1	1.0	1.0	0	0.6	0.7	0	0.5	0.4	1	0.6	0.7
20	2	0.8	0.8	0	0.4	0.5	0	0.4	0.3	1	0.4	0.6
21	0	0.6	0.6	1	0.3	0.4	0	0.3	0.2	1	0.3	0.4
22	0	0.4	0.5	0	0.2	0.3	0	0.2	0.2	0	0.2	0.3
23	0	0.3	0.4	1	0.1	0.2	0	0.2	0.1	0	0.2	0.3
24	0	0.2	0.3	1	0.1	0.2	0	0.1	0.1	0	0.1	0.2
25	0	0.2	0.2	0	0.1	0.1	0	0.1	0.1	0	0.1	0.2
26	1	0.1	0.2	0	0.1	0.1	0	0.1	0.1	0	0.1	0.2
χ^2			29.4		11.3	15.2		13.4	10.7		19.4	21.4
$P(\chi^2)$			0.01		0.50	0.20		0.30	0.50		0.05	0.05
q			0.78		0.75	0.75		0.75	0.75		0.75	0.75
a			1.58		2.075	2.075		1.087	1.087		2.075	2.075

NOTES AND NEWS

Association of British Climatologists—New Directory

We have received a letter from the Association of British Climatologists informing us that the 'Second Directory of British Climatologists' (see the *Meteorological Magazine*, February 1975, page 60) is now available.

The 'Second Directory of British Climatologists' catalogues details of active research climatologists in this country at the end of 1974, their fields of interest and recent publications. It is divided into two sections: Section A consists of a list of institutions and their research interests (the section is subdivided into Institutes of Higher Education, Research Institutes and Related Bodies, and unattached Individuals); Section B lists research publications by individuals up to the end of 1974.

The 58-page Directory is available at a cost of 50 pence from the Hon. Treasurer of the Association, Dr E. M. Frisby, 10 The Larches, Headington, Oxford.

OBITUARY

It is with regret that we have to record the death of Mr E. C. W. Goldie, Assistant Scientific Officer, Met o 9, on 14 August 1975.

CORRECTION

Meteorological Magazine, September 1975, p. 258, line 29, for '0°C at 2.5 km' read '0°C at 0.5 km'.

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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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