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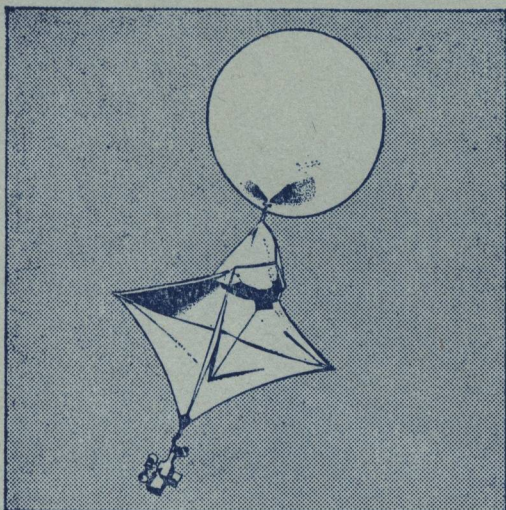
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A REGRESSION TECHNIQUE FOR OBJECTIVE FORECASTS AT 300 MILLIBARS

By A. WOODROFFE

Summary.—A regression equation technique is described for deriving forecasts at 300 mb from the results of a three-parameter numerical forecasting model. The accuracy of the forecasts is discussed and a comparison made with the 300 mb forecasts prepared by conventional methods.

Introduction.—The movement and development of large-scale atmospheric systems can be forecast by numerical methods but the necessary computations can only be performed in a reasonable time if a relatively simple model is used to represent the complex atmospheric structure. The basic variables in such a model may be the contour height fields at a few discrete pressure levels. In formulating the model a compromise is reached between the overall forecast requirements and the complexity of the model in relation to the computing facilities available, with the result that possibly not all the desired levels can be included.

The Meteorological Office operational numerical forecasting scheme is based on an improvement of the three-parameter model,¹ which predicts the contour heights at 1000, 500 and 200 mb. The 200 mb surface is identified with the tropopause and the assumption is made that the motion of air across this upper isobaric surface is negligible. Past results have shown the 500 and 200 mb numerical forecasts to be more accurate than the manually drawn charts, so that there is already a case for basing forecast procedures entirely on computed prontours. However, one of the most important forecast charts at the present time, particularly for aviation purposes, is that for the 300 mb level. Objective forecasts for 300 mb will ultimately be produced by using a multi-layer model and a programme which carries data and computes the height fields for all the required levels. At present, though, other techniques must be used.

This paper describes an objective method for obtaining 300 mb forecasts from the results of the three-parameter model, and compares their accuracy relative to the Central Forecasting Office (CFO) forecasts.

Method.—Accurate wind forecasts are especially important at 300 mb, since the cores of jet streams very often lie near this level. The numerical model already provides forecasts at 1000, 500 and 200 mb but direct interpolation between 500 and 200 mb is not possible because in temperate

latitudes the tropopause is generally found between these two levels. Winds at 300 mb are usually stronger than at either 500 or 200 mb. Good representation of jet streams is desirable in producing forecasts for aviation although it must be remembered that any technique based on numerical methods cannot include detail on a scale less than the grid length used (about 200 miles).

A simple and direct approach to the problem is to use some form of multi-level regression equation to predict the 300 mb contour height, (h_{300}), at each grid point in terms of numerically forecast parameters. An example would be

$$h_{300} = F(h_{1000}, h_{500}, h_{200}) \quad \dots (1)$$

where F is the function of the forecast heights (h_{1000} , h_{500} and h_{200}) which are obtained from the three-parameter model for the 1000, 500 and 200 mb levels at the grid point. It is mathematically convenient to work in terms of D -values (height departures from the standard values), thus

$$D_{300} = F(D_{1000}, D_{500}, D_{200}). \quad \dots (2)$$

A method² of this type has been tried in the United States with some success, using a simple linear regression equation of the form :

$$D_{300} = K + a D_{850} + b D_{500} + c D_{200}. \quad \dots (3)$$

Results have been obtained from such a multi-level regression study based on 16,307 reports covering the period March-May 1962. No geographical division was attempted, but it appears that the majority of the reports used in the analysis were from the United States and Canada. The regression equation obtained was :

$$D_{300} = -5.9 - 0.298 D_{850} + 0.991 D_{500} + 0.394 D_{200} \quad \dots (4)$$

where the D -values are in metres.

A test of this equation on 1362 independent reports in May 1962 showed a root mean square error in the predicted values of D_{300} of 22.4 metres (compared with 22.2 m for the dependent data).

The first step in developing a 300 mb forecast procedure for use in CFO was to form a set of suitable regression equations. The numerical forecasts produced using the three-parameter model extended over the area indicated in Figure 1. In this preliminary investigation it did not seem desirable to embark on a complex statistical analysis covering a large number of stations, so Ocean Weather Station (OWS) A (62°N 33°W), Crawley and Gibraltar were taken as representative of the whole area. These stations were chosen in particular because firstly they incorporated a wide range of latitude which it was hoped would indicate how the coefficients varied with position, and secondly these radiosonde observations were available on punched tape in a form suitable for analysis on a computer. Observations at 0000 GMT and 1200 GMT over the period January 1961-June 1962 were analysed for each station and sets of 1000, 500, 300 and 200 mb D -values were extracted on METEOR (a Ferranti Mercury computer). If any levels were missing on a particular occasion, the report was not used. Approximately 900 sets of data were extracted for each of the three stations.

The form of the regression equation to be fitted to the data was :

$$D_{300} = k + a D_{1000} + b D_{1000}^2 + c D_{500} + d D_{500}^2 + e D_{200} + f D_{200}^2. \quad \dots (5)$$

The coefficients k , a , b , c , d , e , and f were considered to be constant for a particular station (no seasonal variation). The programme which computed

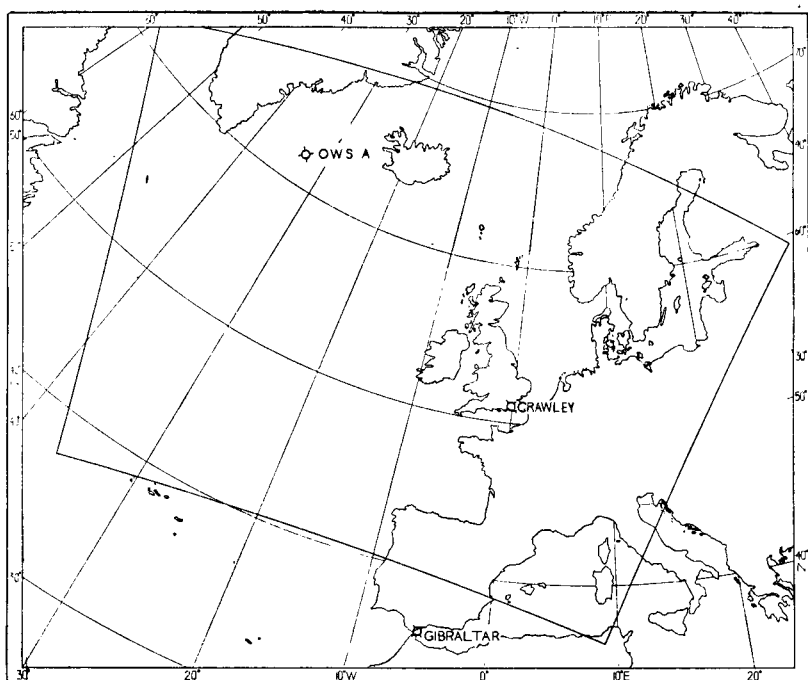


FIGURE 1—KEY STATIONS AND FORECAST AREA

the regression equations giving the best fit to the data also tested that each term was statistically significant using Student's t-test. If any of the terms were not significant at the 5 per cent level, the least significant predictor was rejected and the equation recomputed. This process was repeated until all the remaining terms were significant. The equations obtained in this way for the three stations were as follows (with D -values in metres) :

$$\begin{aligned} \text{OWS A} \quad D_{300} = & 6.6 - 0.223 D_{1000} + 1.039 D_{500} + 0.000075 D_{500}^2 \\ & + 0.340 D_{200}, \quad \dots (6) \end{aligned}$$

$$\begin{aligned} \text{Crawley} \quad D_{300} = & 3.5 - 0.207 D_{1000} + 0.000362 D_{1000}^2 + 0.908 D_{500} \\ & - 0.000470 D_{500}^2 + 0.402 D_{200} + 0.000125 D_{200}^2, \quad \dots (7) \end{aligned}$$

$$\begin{aligned} \text{Gibraltar} \quad D_{300} = & -11.0 - 0.222 D_{1000} + 0.000837 D_{1000}^2 + 0.906 D_{500} \\ & - 0.000647 D_{500}^2 + 0.494 D_{200}, \quad \dots (8) \end{aligned}$$

The root mean square errors in predicting D_{300} using equations (6), (7) and (8) on the dependent data were respectively 31.3, 24.6 and 16.6 m (overall root mean square error 24.9 m). A second set of equations were computed to fix the D -value profile more precisely by including 100 mb D -values as well. Forecast D -values are not readily available at present but changes in the 100 mb pattern are usually slow and therefore the actual D_{100} -values could be used in the forecast regression equation. In the fairly near future it is hoped that objective analyses of the 100 mb surface will be produced on a routine basis so that actual D_{100} grid-point values will be readily available.

The form of the second set of equations is :

$$D_{300} = k + a D_{1000} + b D_{1000}^2 + c D_{500} + d D_{500}^2 + e D_{200} + f D_{200}^2 + g D_{100} + h D_{100}^2 \quad \dots (9)$$

The corresponding equations for the three stations are :

$$\text{OWS A} \quad D_{300} = 20.9 - 0.178 D_{1000} + 0.752 D_{500} + 0.705 D_{200} - 0.191 D_{100} \quad \dots (10)$$

$$\text{Crawley} \quad D_{300} = 11.2 - 0.174 D_{1000} + 0.714 D_{500} - 0.000256 D_{500}^2 + 0.672 D_{200} - 0.172 D_{100} \quad \dots (11)$$

$$\text{Gibraltar} \quad D_{300} = -9.0 - 0.133 D_{1000} + 0.789 D_{500} - 0.000491 D_{500}^2 + 0.627 D_{200} - 0.130 D_{100} \quad \dots (12)$$

The root mean square errors in D_{300} for the dependent data are respectively 25.0, 20.2 and 14.6 m (overall root mean square error 20.4 m). These figures compare favourably with the value of 22.2 m from the American spring season regression equation (4), even though equations (10), (11) and (12) apply throughout the year. It seems that the inclusion of information at 100 mb largely compensates for using the same regression coefficients throughout the year. The choice of the three key stations implied that apart from seasonal variation, one of the factors determining the coefficients at any point in the forecast area is the latitude. Inspection of equations (10), (11) and (12) reveals fairly small and reasonably consistent differences between the coefficients for the three stations, even though there is a difference in latitude of 26° between OWS A and Gibraltar. The assumption has therefore been made that over the forecast area shown in Figure 1, the coefficients can be considered as constant along a given latitude circle. Moreover it is assumed that for any grid point which lies between 62°N and 36°N a prediction equation can be formed by taking a weighted mean of the coefficients for the two nearest key stations, the weighting being inversely proportional to the latitude difference between the key station and the grid point concerned. Outside this latitude range, the equation appropriate to the nearest key station can be used.

With these simple assumptions, equations (10), (11) and (12) form a set which may be used to compute the 300 mb contour field over the area of Figure 1, given the fields at 1000, 500, 200 and 100 mb. Note that the only second power term in the equations is D_{500}^2 . The other second order terms were at best only marginally significant and were consequently eliminated.

Accuracy of the equations.—It was shown in the previous section that a root mean square error of the order of 20 m is associated with the prediction equations (10), (11) and (12). If the 1000, 500, 200 and 100 mb heights used as predictors are forecast numerically (or a persistence forecast is used in the case of the 100 mb level), the overall error in computing the forecast height at 300 mb will arise from errors in the numerical forecast and from using the regression equation. The total error will depend on the correlations between the various sources of error.

Now the thickness forecasts by the three-parameter model are generally better than the prontours, a fact which suggests a positive correlation between the errors at different levels. However estimates can be made of the likely total error assuming firstly no correlation and secondly correlation coefficients of $+1$ between the numerical forecast errors at 1000, 500 and 200 mb.

It will also be assumed that the regression equation errors and 100 mb persistence errors are not correlated either with errors at the other levels or with each other. This is certainly not strictly true in practice, but should be sufficiently accurate for this calculation.

An assessment of the errors associated with the use of equations (10), (11) and (12) may be made by considering the following approximate expression for D_{300} :

$$D_{300} = -0.17 D_{1000} + 0.75 D_{500} + 0.67 D_{200} - 0.17 D_{100}. \quad \dots (13)$$

The contribution from D_{500} can be neglected as it is most often only a minor correction term. Let ϵ_p represent the error in the height at the pressure level p mb.

(a) Assuming no correlation between errors at different levels

$$\epsilon_{300}^2 = (0.17 \epsilon_{1000})^2 + (0.75 \epsilon_{500})^2 + (0.67 \epsilon_{200})^2 + (0.17 \epsilon_{100})^2 + \epsilon_R^2. \quad \dots (14)$$

where ϵ_R is the root mean square height error (estimated as 20 m) associated with the regression equation. Statistics for the 24-hour forecasts by the three-parameter model over the period January–September 1963 give :

$$\epsilon_{1000} \simeq 40 \text{ m}, \epsilon_{500} \simeq 40 \text{ m}, \epsilon_{200} \simeq 50 \text{ m}.$$

Also, from some work done in the Meteorological Office on forecasting at 100 mb :

$$\epsilon_{100} \simeq 50 \text{ m for a 24-hour persistence forecast.}$$

Thus $\epsilon_{300}^2 \simeq (0.17 \times 40)^2 + (0.75 \times 40)^2 + (0.67 \times 50)^2 + (0.17 \times 50)^2 + 400$,
therefore $\epsilon_{300} \simeq 50 \text{ m}.$

(b) Assuming perfect correlation between ϵ_{1000} , ϵ_{500} and ϵ_{200}

$$\epsilon_{300}^2 \simeq [(-0.17 \times 40) + (0.75 \times 40) + (0.67 \times 50)]^2 + (0.17 \times 50)^2 + 400, \quad \dots (15)$$

therefore $\epsilon_{300} \simeq 60 \text{ m}.$

Note that the major contributions are from ϵ_{500} , ϵ_{200} and ϵ_R . It can be concluded that the regression equation technique is likely to provide forecasts of 300 mb contour height with a root mean square error exceeding that of the other numerical pronouncements by no more than about 10 m.

Similar calculations can be made for the winds. If the regression coefficients are assumed to be constants, equation (13) reduces, by taking the gradient of both sides, to an equation relating the vector winds (\mathbf{V}_{300} , \mathbf{V}_{1000} , \mathbf{V}_{500} , \mathbf{V}_{200} and \mathbf{V}_{100}) at the various levels :

$$\mathbf{V}_{300} = -0.17 \mathbf{V}_{1000} + 0.75 \mathbf{V}_{500} + 0.67 \mathbf{V}_{200} - 0.17 \mathbf{V}_{100}. \quad \dots (16)$$

Let ϵ'_p represent the corresponding root mean square vector errors in the winds. For the 24-hour forecasts made using the three parameter model :

$$\epsilon'_{1000} \simeq 15 \text{ kt}, \epsilon'_{500} \simeq 15 \text{ kt}, \epsilon'_{200} \simeq 18 \text{ kt}.$$

Taking the most unfavourable situation of perfect correlation between ϵ'_{1000} , ϵ'_{500} and ϵ'_{200} , the wind equation corresponding to equation (15) is :

$$(\epsilon'_{300})^2 \simeq [(-0.17 \times 15) + (0.75 \times 15) + (0.67 \times 18)]^2 + (0.17 \times 15)^2 + (\epsilon'_R)^2 \quad \dots (17)$$

therefore $(\epsilon'_{300})^2 \simeq 435 + (\epsilon'_R)^2. \quad \dots (18)$

If $\epsilon'_R=0$, $\epsilon'_{300}\approx 21$ kt,
 if $\epsilon'_R=10$ kt, $\epsilon'_{300}\approx 23$ kt,
 and if $\epsilon'_R=15$ kt, $\epsilon'_{300}\approx 25.5$ kt.

The value of ϵ'_R (the root mean square vector error in the predicted 300 mb wind due to the regression equation) will depend on the variation between ϵ_R at adjacent grid points. If ϵ_R varied very gradually over the whole chart, then ϵ'_R would approximate to zero. Since the predictors are obtained from smoothed fields, random fluctuations in the errors are likely to be quite small. More important will be the error pattern associated with the different synoptic-scale systems, having a typical dimension of 3–5 grid lengths. The quality of the wind forecasts would be seriously impaired if the regression equation errors were systematically distributed, so that, for example, contour heights on the cold side of a jet were consistently overestimated, while those on the warm side were underestimated. With this in mind, 75 cases were analysed where a jet stream (with wind speeds greater than 120 kt) was indicated on the CFO 300 mb chart between OWS A and OWS C (52.7°N 35.5°W). The period chosen was April–December 1963 and easterly jets were not considered. A regression equation was formed for OWS C by the method outlined in the previous section. D_{300} was calculated for the two stations by substituting the subjectively analysed values of D_{1000} , D_{500} , D_{200} and D_{100} into the appropriate equation. The computed values of D_{300} were then compared with the height drawn at each station on the 300 mb chart; the results are summarized in Table I.

TABLE I—JET-STREAM ANALYSIS

	OWS A	OWS C <i>metres</i>	Difference*
Mean observed 300 mb D -value	-356	131	487
Mean error in calculated D_{300}	+4.9	-10.0	-14.9
Root mean square error in calculated D_{300}	22.5	19.6	—
Root mean square error in calculated D_{300} height-difference	—	—	32.0
Mean observed 200 mb height-difference	—	—	420

* Difference for OWS C minus OWS A

The regression equations tended to underestimate the mean component flow in the region of the jet streams by about 3 per cent (see difference column in Table I). However, an error of this magnitude is of no great concern, and could always be overcome by means of an empirical correction. An interesting feature of the results is that the root mean square errors in the predicted values of D_{300} at both OWS A and OWS C were lower than the errors associated with equations (10) and (11), using the dependent data. Note also that the mean flow at 200 mb was on average about 13 per cent less than at 300 mb.

The regression equations were next tested on some actual charts. Grid-point contour heights at 1000, 500, 200 and 100 mb were read from CFO analyses for several selected days in 1963, and the equations were used to compute the corresponding 300 mb fields. The objective analyses prepared in this way were compared with the actual 300 mb charts, and a note was made of any errors which recurred in association with particular synoptic features. Figures 2 and 3 show examples of a winter and summer situation respectively, together with the error fields. The main interest is in the gradient of the isopleths in Figures 2(b) and 3(b), since this indicates the magnitude of the

wind errors due to the regression equations (i.e. ϵ'_R). The error fields shown in these diagrams were actually calculated using the amended D^2_{500} term described in the next paragraph but the amendments were generally slight on these occasions.

There was a tendency to overestimate wind speeds in middle latitudes in areas of large negative D -values ; subsequently it was found that the excessive gradients arose from the D^2_{500} term in the regression equations. Normally, the contribution from this term does not exceed 30 or 40 m at 50°N and decreases to zero at 62°N (latitude of OWS A), but in certain winter situations when very low contour values penetrate well south it can locally exceed 100 m. The unrealistic wind field which then results shows that there is a definite need to limit the contributions from this term on those occasions. The coefficient d in equation (9) must therefore be multiplied by an additional factor ζ , where ζ approximates to unity for the normal range of D -values (-400 m to $+400$ m) found in middle and low latitudes, and decreases in such a manner outside this range that the maximum contribution from D^2_{500} is limited to about 40 m. A suitable form for ζ is :

$$\zeta = \frac{100^2 - D^2_{500}}{100^2 + D^2_{500}}. \quad \dots (19)$$

Table II shows the effect of this additional factor on the D^2_{500} contribution at Crawley ($d = 0.000256$). The revised form of equations (11) and (12) is :

$$\text{Crawley} \quad D_{300} = 11.2 - 0.174 D_{1000} + 0.714 D_{500} - 0.000256 \zeta D^2_{500} + 0.672 D_{200} - 0.172 D_{100} \quad \dots (20)$$

$$\text{Gibraltar} \quad D_{300} = -9.0 - 0.133 D_{1000} + 0.789 D_{500} - 0.000491 \zeta D^2_{500} + 0.627 D_{200} - 0.130 D_{100}. \quad \dots (21)$$

TABLE II—THE MODIFYING FACTOR ζ AND ITS EFFECT

D_{500} metres	Normal contribution (dD^2_{500}) metres	Modifying factor (ζ)	Adjusted contribution (ζdD^2_{500}) metres
0	0	1.00	0
100	3	0.98	3
200	10	0.92	9
300	23	0.83	19
400	41	0.72	30
500	64	0.60	38
600	92	0.47	43
700	125	0.34	43

Cut-off cold pools at 300 mb (often associated with occluded depressions) are difficult to deal with satisfactorily, since on some occasions the bulk of the cold air is located between 500 and 300 mb. Above, there is often a low tropopause with relatively warm air in the lower stratosphere, so that by the time the 200 mb level is reached, the effects of the cold layer have been partially cancelled by the warmer air. Thus there may be little indication either from D_{500} or D_{200} as to the precise value of D_{300} . No real solution to this problem has been found, and in summer months, particularly, the regression equations slightly underestimate the depth of these cold centres. A typical example is the cold pool centred just to the north of Scotland in Figure 3(a). However, the associated error field (Figure 3(b)) shows that the wind errors are restricted to a narrow band around the centre, so that the broad-scale effects are not serious.

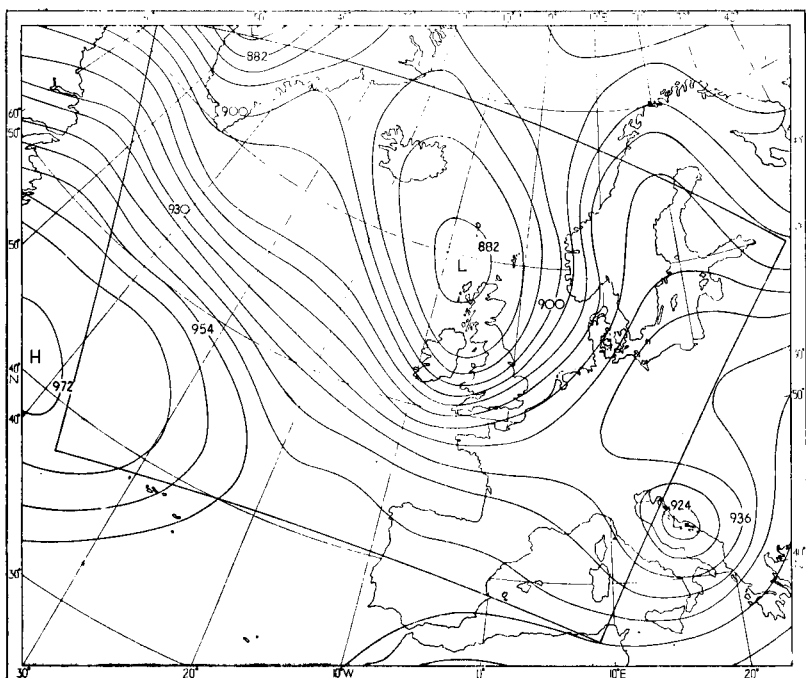


FIGURE 3 (a)—CFO 300 MB ANALYSIS FOR 0000 GMT ON 9 SEPTEMBER 1963
Contours are in decametres.

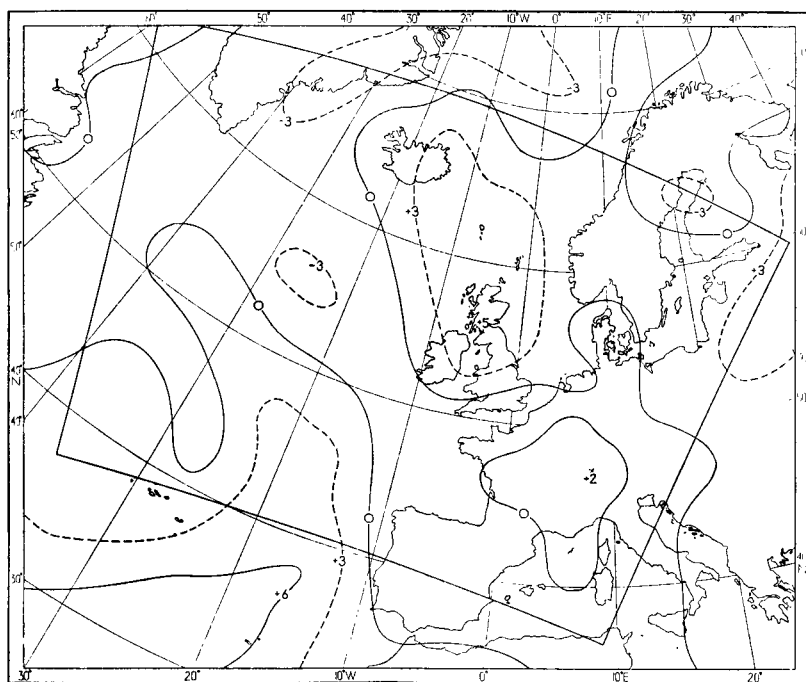


FIGURE 3 (b)—ERRORS IN OBJECTIVE 300 MB ANALYSIS FOR 0000 GMT ON 9
SEPTEMBER 1963
Objective height - CFO analysis height in decametres.

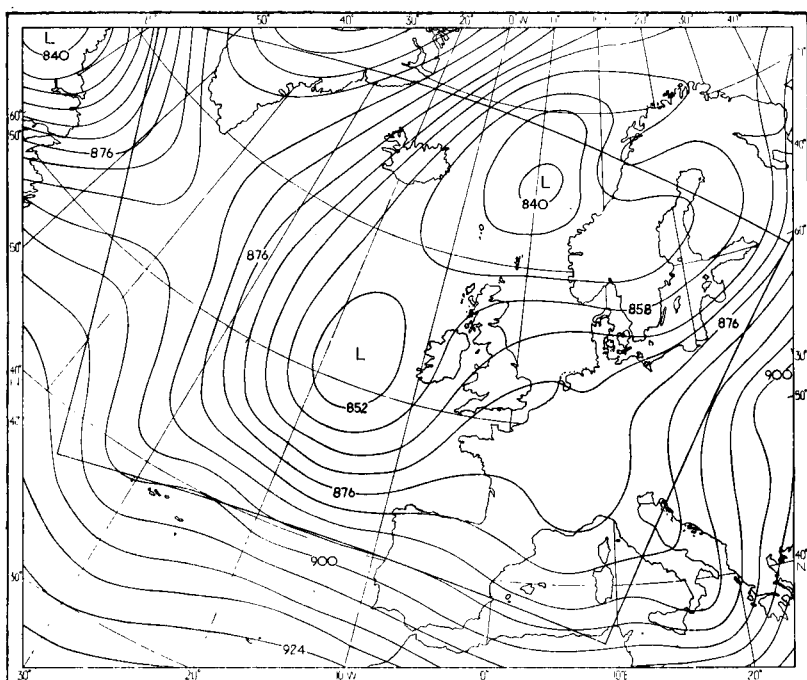


FIGURE 2(a)—CFO 300 MB ANALYSIS FOR 1200 GMT ON 5 FEBRUARY 1963
Contours are in decametres.

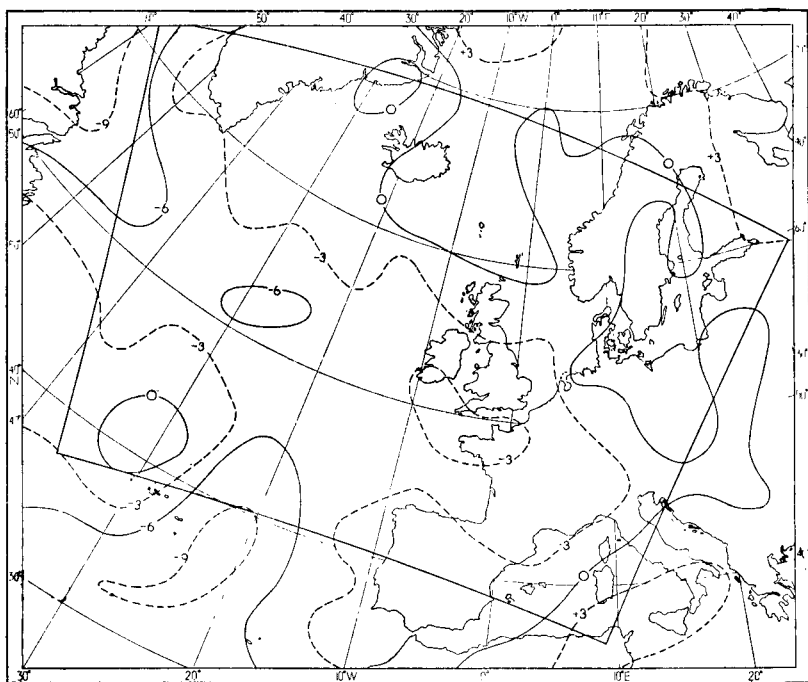


FIGURE 2 (b)—ERRORS IN OBJECTIVE 300 MB ANALYSIS FOR 1200 GMT ON 5
FEBRUARY 1963
Objective height - CFO analysis height in decametres.

Subjective examination indicated satisfactory overall agreement between the actual and objective 300 mb charts, with ϵ'_R probably not exceeding 10 kt. Substituting in equation (18), we obtain an estimate for the total root mean square vector wind error in the 300 mb objective wind forecasts of $\epsilon'_{300} \approx 23$ kt.

Over the period January–September 1963, in a collection of about a hundred CFO 24-hour prontours for 200 mb, the root mean square vector wind error was 23.3 kt. It is extremely unlikely that the CFO errors at 300 mb were less than this and they were probably larger because wind speeds at 300 mb were higher than at 200 mb. It is to be expected, therefore, that the regression technique should provide wind forecasts at 300 mb which are at least as good as the CFO products.

Statistical assessment of the objective forecasts at 300 mb.—The primary purpose of the regression technique, as was stated earlier, is to compute 300 mb prontours from the results of the operational model. Basic data for such calculations were available from the series of operational numerical forecasts made on most weekdays over the period August 1962–October 1963. The 24-hour forecast fields at 1000, 500 and 200 mb, which had been stored on punched paper tape, could be fed directly into the computer. However the use of a 24-hour persistence forecast at 100 mb meant that grid-point heights for 100 mb had to be extracted from the CFO analysis for the initial time (0000 GMT), and then punched on paper tape for input. The 300 mb prontours obtained from the regression equations were verified statistically, and compared with the corresponding forecasts made by conventional methods in CFO.

The ordinary 24-hour numerical forecasts are usually verified against the objective analysis for 0000 GMT produced on the next day. In cases where this is not possible (e.g. no operational experiment on Saturday or Sunday), the CFO subjective analysis is used as the standard against which the forecasts are checked, and it has been shown that the statistics depend to a slight extent on whether the comparison is made with an objective or subjective analysis. Since no 300 mb objective analyses were available, to ensure that any comparisons were completely unbiased, it was convenient to select only occasions when the computed 500 and 200 mb prontours had also been verified against subjective analyses. This requirement restricted the cases mainly to forecasts for 0000 GMT on Saturday computed on Friday.

Forecasts for 300 mb were computed for 25 such occasions which occurred over the period January–June 1963. The results, together with the corresponding CFO statistics for 500, 300 and 200 mb are summarized in Table III. The statistics refer to 192 grid points covering the area shown in Figure 1. Mean winds over a grid square were calculated using the geostrophic assumption.

Table III shows that there is little to choose between the root mean square height errors for the objective and CFO prontours for 300 mb. However, the main interest is in the wind errors and it is clear that here the general superiority of the numerical products at 500 and 200 mb has been retained in deriving the 300 mb fields. The error in the numerical prontours at 300 mb is 4.6 kt greater than the numerical error in 200 mb prontours, and is in accordance with the estimate made in the previous section (page

TABLE III—STATISTICS FOR 25 OCCASIONS IN JANUARY–JUNE 1963

	500 mb		300 mb		200 mb	
	Numerical	CFO	Numerical	CFO	Numerical	CFO
Root mean square height error (m)	52.7	57.5	79.3	79.9	70.5	70.1
Root mean square vector wind error (kt)	18.6	22.8	25.9	30.2	21.3	24.6
Mean maximum height error (m)	150	162	192	209	179	182
Mean maximum vector wind error (kt)	49.7	60.9	65.8	77.0	56.4	62.5
Correlation between height and height-error	-0.03	-0.05	-0.02	-0.02	-0.12	-0.08
(Forecast – actual) kinetic energy equivalent wind error (kt)	-17.4	-8.0	-21.2	-10.4	-13.0	-2.7

138), using equation (18). At 200 mb, the root mean square vector wind error for the computed charts is 13 per cent lower than the CFO figure. At 500 mb, the level of minimum error in the computed winds, the proportion is 18 per cent lower, while at 300 mb it is 14 per cent lower than the CFO figure. Thus, relative to CFO, the 300 mb objective pronouncements show about the same skill in forecasting winds as the 200 mb numerical pronouncements. The mean maximum grid-point height error and the mean maximum vector wind error (evaluated over a grid square) are also recorded in Table III.

The results indicate that there is negligible correlation between the height error and the actual contour height for both the conventional and objective forecasts at 300 mb. The absence of any such bias provides further justification for the broad assumptions made in forming the equations for individual grid points from the equations for the three key stations.

The values of (forecast – actual) kinetic energy equivalent wind error (x) in Table III are calculated from :

$$x^2 = W_f^2 - W_A^2 \quad \dots (22)$$

where W_f is the root mean square forecast wind speed over the verification area, and W_A is the root mean square actual wind speed over the same area. The statistics of (forecast – actual) kinetic energy equivalent wind in Table III show clearly the loss of energy which occurs in the process of numerical computations. If the magnitude of x is large, the strength of jet streams, where the bulk of the kinetic energy is concentrated, will not be forecast satisfactorily. The root mean square actual winds at 500, 300 and 200 mb were respectively 38.7, 50.4 and 44.8 kt. Allowing for the higher wind speeds at 300 mb, the value of x for the objective 300 mb forecasts (-21.2 kt) compares satisfactorily with -17.4 for the normal computed 500 mb forecast.

It is clear that statistically the objective 300 mb forecasts for these 25 situations were better than the CFO forecasts. Satisfactory subjective comparisons are extremely difficult to make, and none was attempted, but examination of the objective forecasts showed that jet streams were on the whole handled quite well, apart from the slight bias towards weaker flow mentioned previously.

Examples of forecasts.—The objective 300 mb forecasts for 0000 GMT on 2 February and 0000 GMT on 4 May 1963 are shown in Figures 4 and 5. These two situations were selected because in both cases the belts of strong winds were handled considerably better numerically than by CFO. The

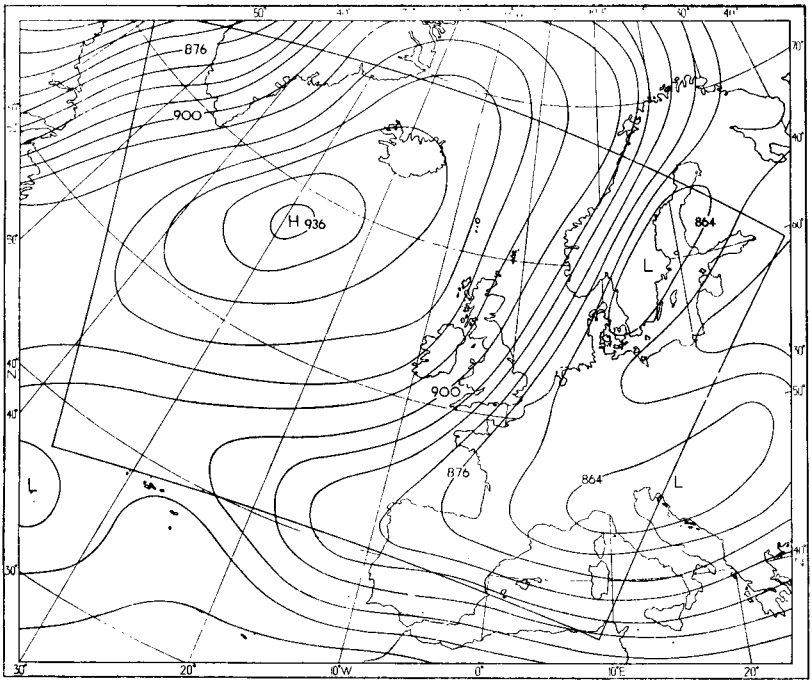


FIGURE 4 (a)—CFO 300 MB ANALYSIS FOR 0000 GMT ON 1 FEBRUARY 1963
Contours are in decametres.

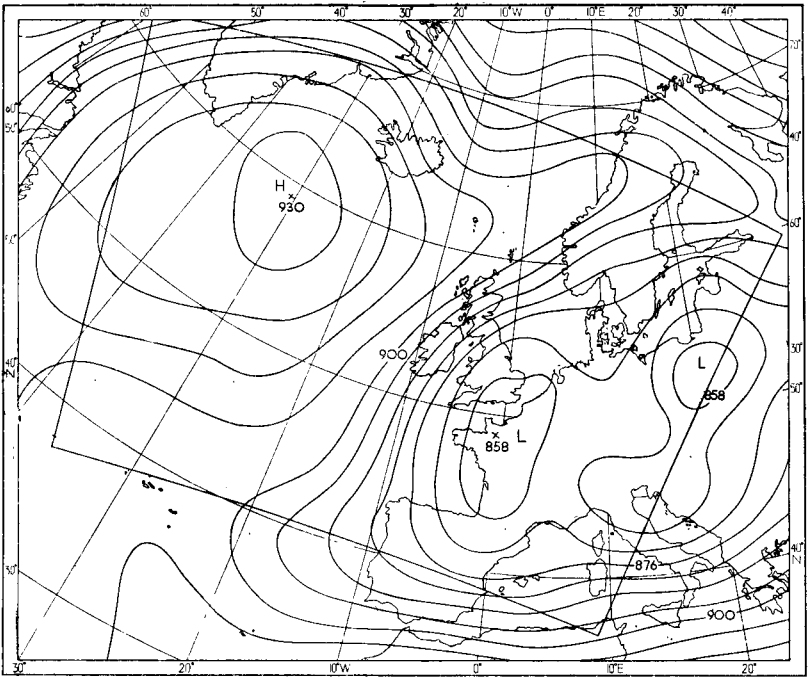


FIGURE 4 (b)—CFO 300 MB ANALYSIS FOR 0000 GMT ON 2 FEBRUARY 1963
Contours are in decametres.

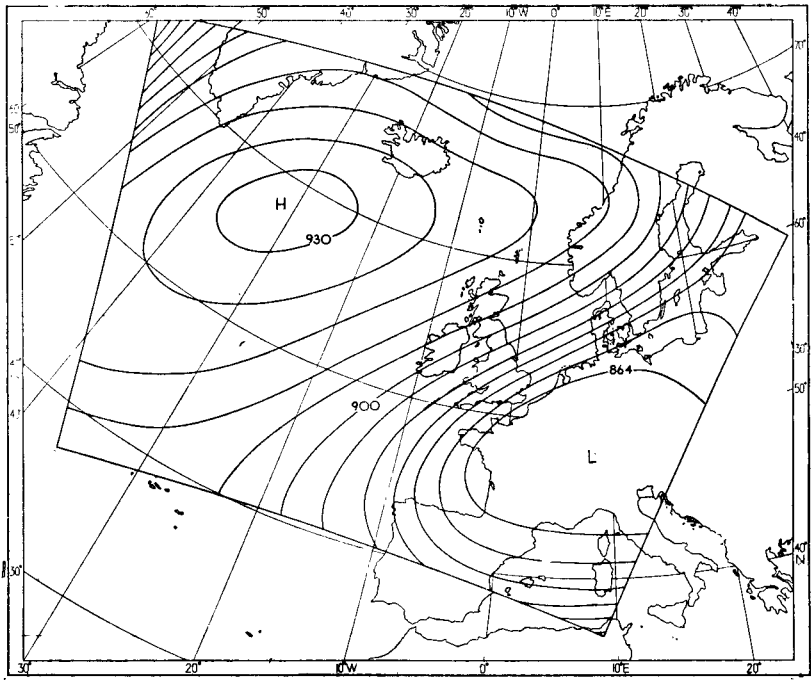


FIGURE 4 (c)—CFO 300 MB FORECAST FOR 0000 GMT ON 2 FEBRUARY 1963
Contours are in decametres.

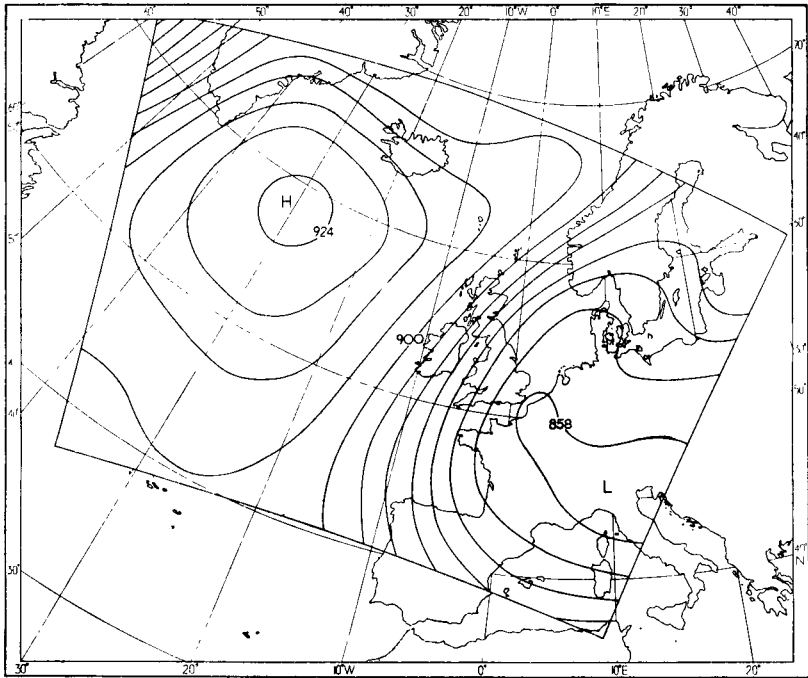


FIGURE 4 (d)—OBJECTIVE 300 MB FORECAST FOR 0000 GMT ON 2 FEBRUARY 1963
Contours are in decametres.

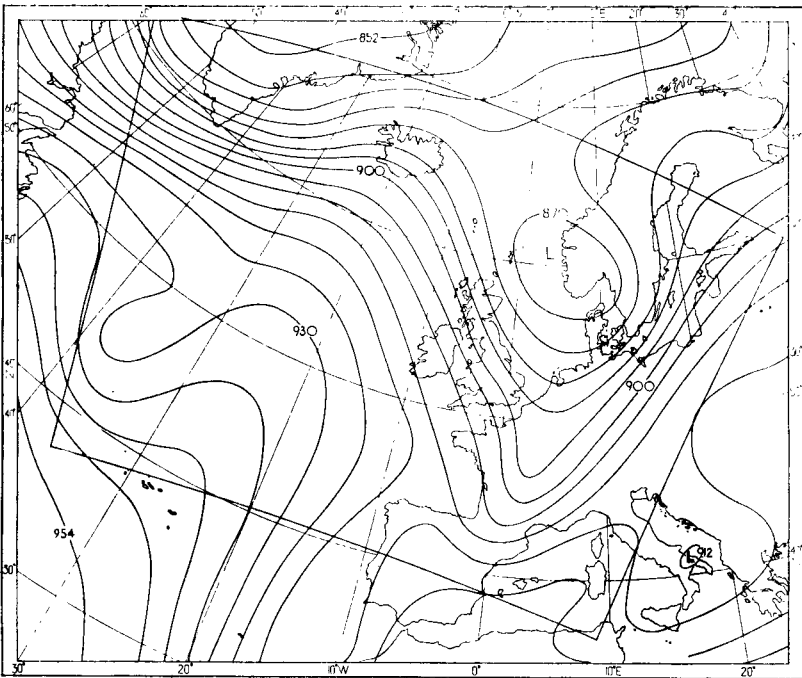


FIGURE 5 (a)—CFO 300 MB ANALYSIS FOR 0000 GMT ON 3 MAY 1963
Contours are in decametres.

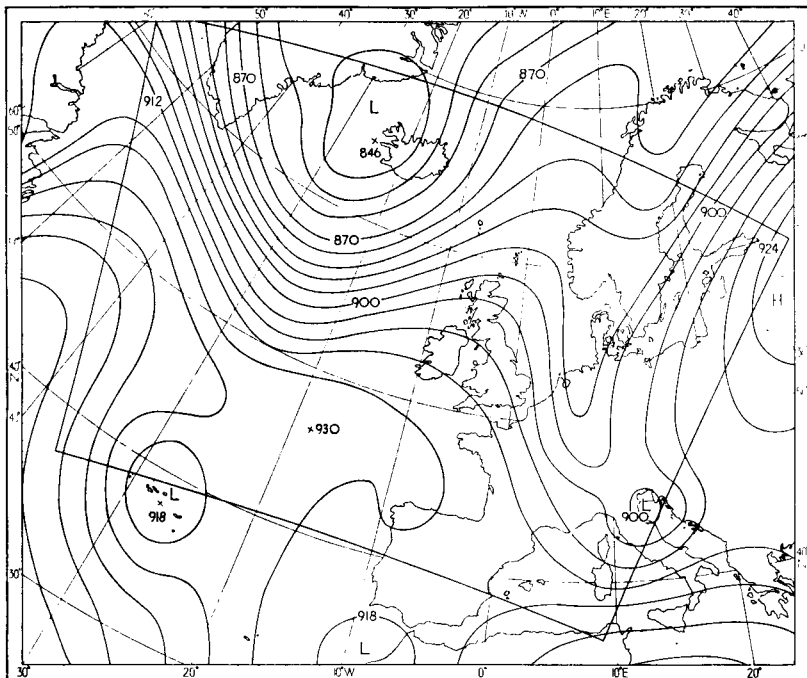


FIGURE 5 (b)—CFO 300 MB ANALYSIS FOR 0000 GMT ON 4 MAY 1963
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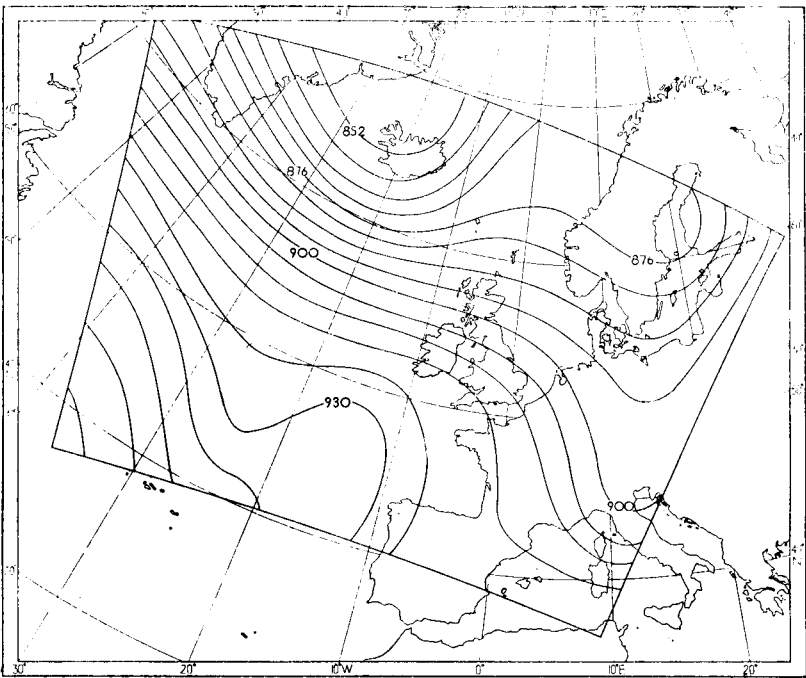


FIGURE 5 (c)—CFO 300 MB FORECAST FOR 0000 GMT ON 4 MAY 1963
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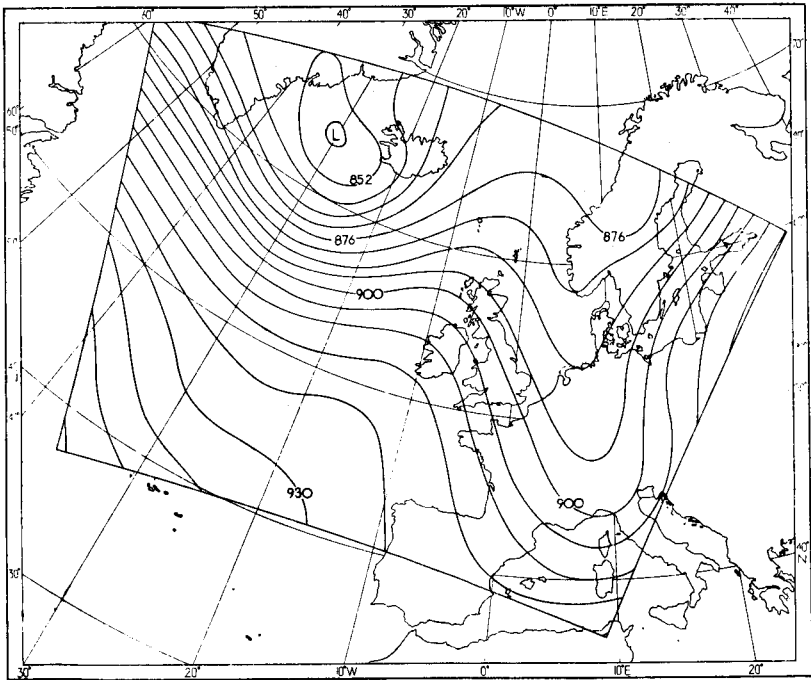


FIGURE 5 (d)—OBJECTIVE 300 MB FORECAST FOR 0000 GMT ON 4 MAY 1963
Contours are in decametres.

success at 300 mb was of course dependent upon successful forecasts at 500 and 200 mb but the examples given show that the regression technique carried the success to the 300 mb forecast.

The CFO analysis for 0000 GMT, 1 February 1963 (Figure 4(a)) shows a substantial block established to the west of the British Isles, with a north-north-east jet over south-east England. Twenty-four hours later (Figure 4(b)) the general situation was very similar, but there were some important changes in the detail of the wind pattern. The development of the low vortex over France had resulted in a slight veering of the jet and a transference north-westwards, with light winds coming in over south-east England. The CFO forecast (Figure 4(c)), although veering the jet, retained the strongest winds over the southern half of the country, but the objective method (Figure 4(d)) forecast the position, strength and orientation of the jet very well.

The 300 mb CFO analyses for 0000 GMT, 3 May and 0000 GMT, 4 May 1963 are shown in Figures 5(a) and 5(b) respectively. The main developments occurred in the Denmark Strait region, where a surface depression which had previously been moving steadily east-north-east in the strong flow over southern Greenland, occluded rapidly and became very slow moving, but deepened by a further 14 mb over the 24-hour period. This resulted in the development of a 300 mb trough just to the west of Iceland, and the veering of the jet near Greenland to north-west. Both the CFO (Figure 5(c)) and the objective forecast (Figure 5(d)) were broadly correct in this area, but the objective method predicted the trough curvature and the strength of the jet more accurately. The weak ridge to the west of the British Isles and the slow-moving downstream trough were also handled better objectively. The CFO forecast was particularly poor in dealing with the downstream trough which was taken too far east over Germany and smoothed out too much. The computed forecast, however, correctly kept the trough almost stationary in the north, while moving the southern portion steadily eastwards into Italy.

Conclusions.—The objective 300 mb forecasts based on the results of the three-parameter model are significantly better than those produced by CFO. This fact together with the convenience of computed charts, presents a strong case for their immediate application in general purpose and aviation forecasting.

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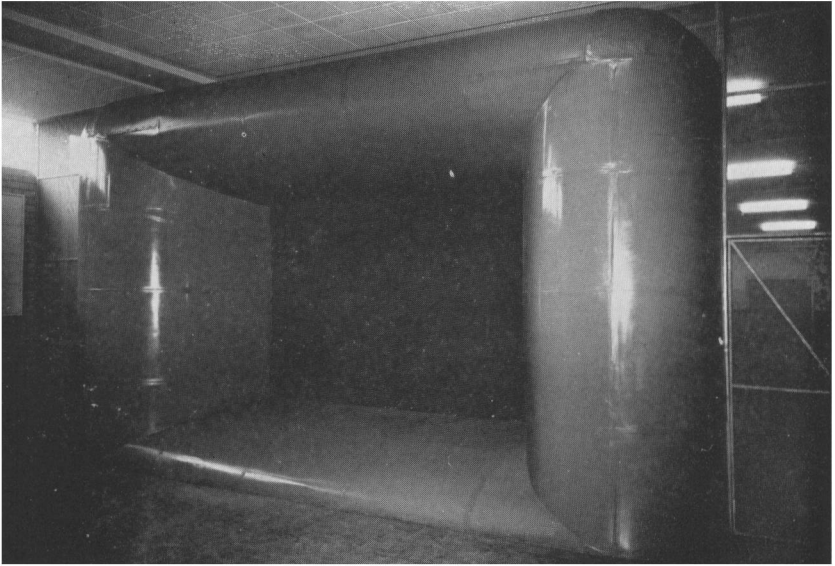
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551.5:061(41-4):533.6.07

WIND-TUNNELS IN THE METEOROLOGICAL OFFICE

By G. E. W. HARTLEY, M.A.

Introduction.—Wind-tunnels are used in the Meteorological Office mainly for checking the performance and calibration of anemometers of various types. Some years ago, when the accepted standard recording anemometer was the pressure-tube anemograph which could be checked by a manometer test, there was no need for a wind-tunnel. Some cup contact and counter anemometers were calibrated in wind-tunnels at the National Physical Laboratory (NPL), and other anemometers of the same type were assumed to be correct



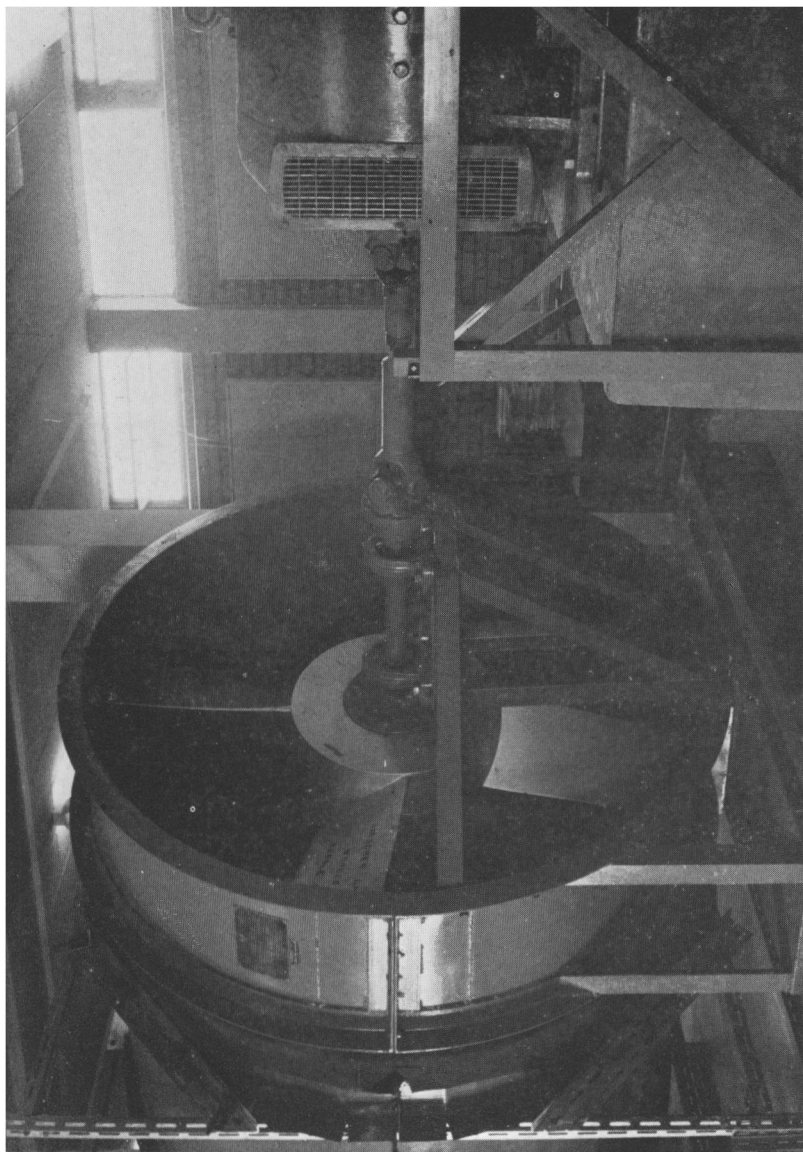
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PLATE I—TUNNEL ENTRANCE AND HONEYCOMB
See page 146.



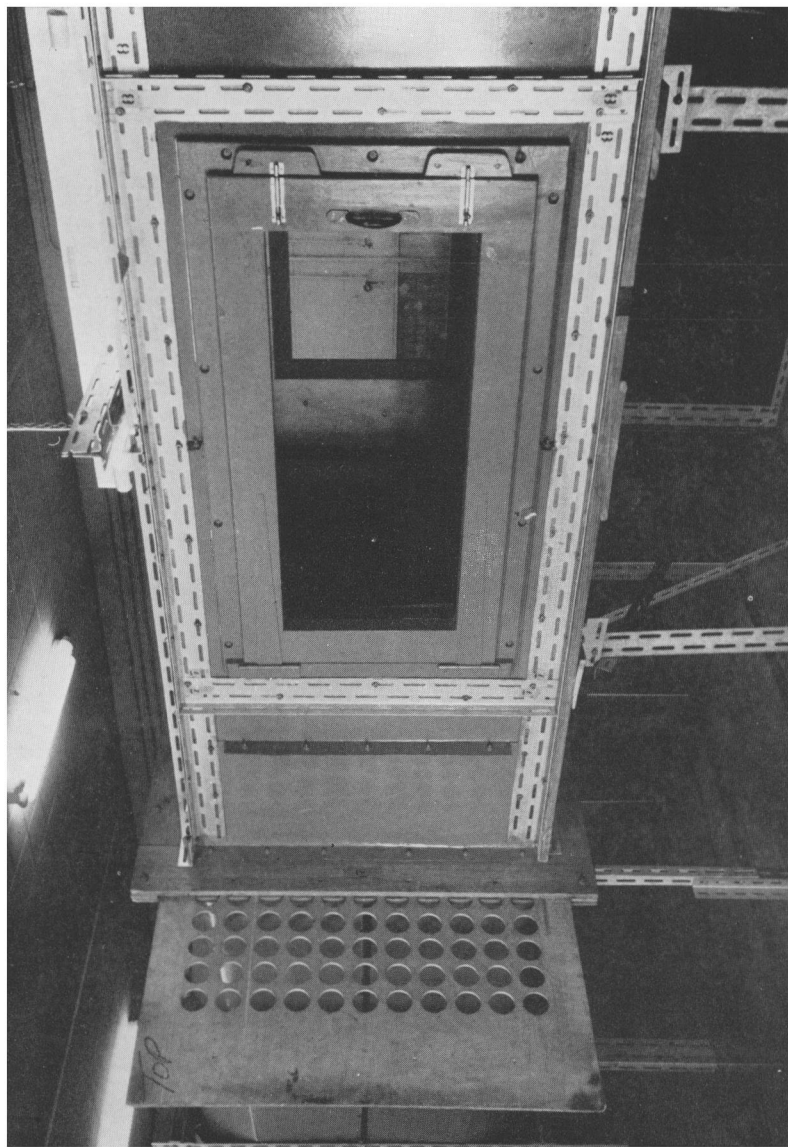
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**PLATE II—WIND-TUNNEL, SHOWING CONSTRUCTION OF EXPANDING SECTION
BETWEEN WORKING SECTION AND FAN**
See page 146.



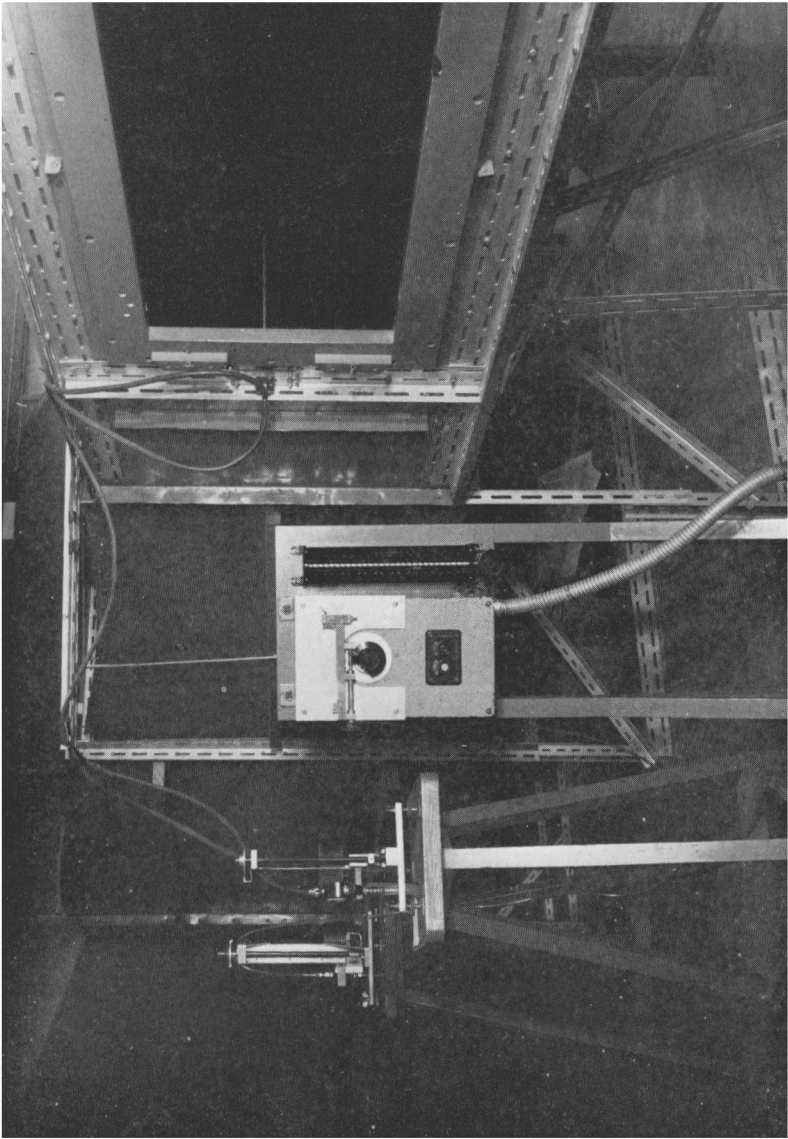
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PLATE III—WIND-TUNNEL FAN, DRIVE SHAFT, AND MOTOR
See page 146.



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PLATE IV—WIND-TUNNEL WORKING SECTION SHOWING DOOR, AND GRID FOR
OBTAINING LOW SPEEDS PARTLY INSERTED
See page 146.



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PLATE V—WIND-TUNNEL MOTOR CONTROL PANEL, PITOT-STATIC TUBE AND
MANOMETER
See page 148.

if they passed a spinning test and if their dimensions agreed with the drawings. When the cup generator anemometer was introduced as standard Meteorological Office equipment it became necessary to carry out calibration tests on all cup anemometers ; the NPL was unable to undertake this work other than an occasional test for some special reason and so it became necessary to have a wind-tunnel as part of Meteorological Office test equipment.

Arrangements at Stonehouse.—

First wind-tunnel.—The first wind-tunnel used in the Meteorological Office was made in 1942 when part of the Office was in Stonehouse, Gloucestershire. It was a rather crude hardboard and wood structure with a working section $2\frac{1}{2}$ ft square and 4 ft long, and a contraction ratio of 4:1; it had a closed working section, and the flow was straight through the tunnel with a return flow around the tunnel room. It had a 10-h.p. constant-speed a.c. motor with a variable-diameter pulley and belt drive to a 4-bladed fan. The tunnel and fan were made in the Meteorological Office workshop ; the motor and variable-speed gear were supplied by an outside firm.

The speed range was about 13 to 40 miles per hour and lower speeds were obtained by inserting grids with evenly-spaced holes downstream of the working section. Speed measurements were made by connecting suction holes in the walls of the contraction upstream of the working section to a sloping-tube liquid manometer.

With this tunnel it was difficult to measure absolute speed in the tunnel, but anemometers of known types could have their calibration checked. It was necessary that one of the type had a known performance (for example by calibration at NPL). The anemometer of known performance was then available to calibrate the manometer, which could then be used as a standard of reference to check the calibrations of other anemometers of the same type.

Second wind-tunnel.—During 1943–44 a second wind-tunnel was designed and made with a view to obtaining higher speeds. This was an open-jet closed return-flow tunnel with a jet 18 inches in diameter, of similar design to the Royal Aircraft Establishment (RAE) 5ft open-jet tunnel,¹ but reduced in size.

This tunnel had a 9-h.p. movable-brush variable-speed a.c. motor with a speed range of 0–3000 r.p.m., driving a 6-bladed wooden fan. Speeds up to 80 miles per hour were obtainable but the distribution of wind speed in the jet was uneven. Though not large enough to calibrate standard cup anemometers it was useful for examining their performance at higher speeds ; and was used for calibration of hand anemometers, thermometer lag tests, radio-sonde windmill tests and other experimental work. It could be fitted with a means of raising the temperature inside.

This tunnel is still in use but when it was moved to Bracknell it was increased in length to give a larger contraction ratio, and fitted with a honeycomb structure upstream of the jet. This improved the flow pattern in the jet but reduced the maximum speed to about 70 miles per hour.

Arrangements at Harrow.—When the Meteorological Office moved from Stonehouse to Harrow both tunnels were brought and set up close together in the sub-basement two floors below ground, where their noise caused no inconvenience. They were so sited that the variable-speed motor

could be used to drive either tunnel by changing the belt drive from one to the other ; this gave the large tunnel a more easily controlled and infinitely variable speed range.

Third wind-tunnel.—In 1949, the design of a larger and more efficient tunnel was considered ; and after consultation with NPL, RAE, and other wind-tunnel users it was decided to make a tunnel with a working section $4\frac{1}{2}$ ft wide by 3 ft high capable of speeds up to 100 knots.

This size of working section was not as large as could be desired, but was the largest which could be accommodated in the space available. There was considerable height limitation and because of this the entrance to the honeycomb section of the tunnel was faired to the floor and ceiling so that the air flowed round the sides of the entrance into the mouth of the tunnel. This wind-tunnel operated at Harrow from 1952 to 1960. When the tunnel was moved to Bracknell it was set 1 ft higher and modified so that air entered from above as well as from both sides. This had no adverse effect on the flow pattern.

Arrangements at Bracknell.—The second and third wind-tunnels were brought to Bracknell in 1960. The general design of the large tunnel as installed at Bracknell is shown in Figure 1. It has the following principal dimensions : tunnel entrance 9 ft wide by 6 ft high with faired entry curves and honeycomb (see Plate I) ; a parallel-sided section 9 ft by 6 ft by 4 ft long ; a contraction 12 ft long changing the section to $4\frac{1}{2}$ ft wide by 3 ft high ; a working section $4\frac{1}{2}$ ft wide and 3 ft high and 8 ft long ; an expanding section 15 ft long changing to a 24-sided regular polygonal section 6 ft $\frac{1}{2}$ inch across opposite flats (see Plate II).

A 4-bladed wooden fan (see Plate III) revolving in a metal ring flexibly connected to the end of the tunnel is directly driven by a d.c. electric motor.

The methods and materials of construction of the tunnel were dictated by the availability of men and materials at the time. It was easier to obtain sheet steel and slotted angle than to obtain wood and there were a number of metal workers available and only one carpenter. Furthermore it was known that a move from Harrow would be made quite soon after completion of the tunnel, and so it was designed to be made in fairly small sections which could be prepared in the workshop, assembled in the tunnel room and subsequently taken apart again for moving.

The main skin of the tunnel is made from 21 s.w.g. mild steel sheet in sections cut from sheets 6 ft by 3 ft. Each piece has bent-over flanges with bolt-holes for bolting to adjoining pieces, the joints being sealed on the inside by adhesive tape. The skin is supported at intervals by frames made from slotted angle (see Plate II). Where there are curves in the contraction section the steel sheet is screwed to wooden frames of the correct contour.

The working section has a floor of 1-inch thick wood with $\frac{1}{2}$ -inch hardboard above ; its sides consist of hinged doors with $\frac{1}{4}$ -inch thick clear plastic window panels (see Plate IV) ; and there are clear plastic panels in the roof of the working section for illumination.

In the centre of the floor of the working section there is a hole and means of fixing in it bosses of various sizes to hold pillars on which are mounted instruments for test.

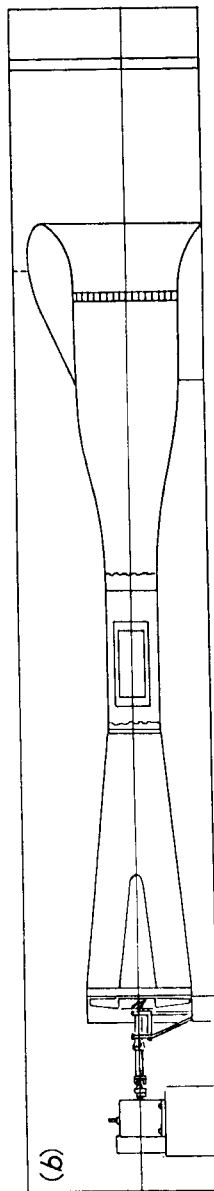
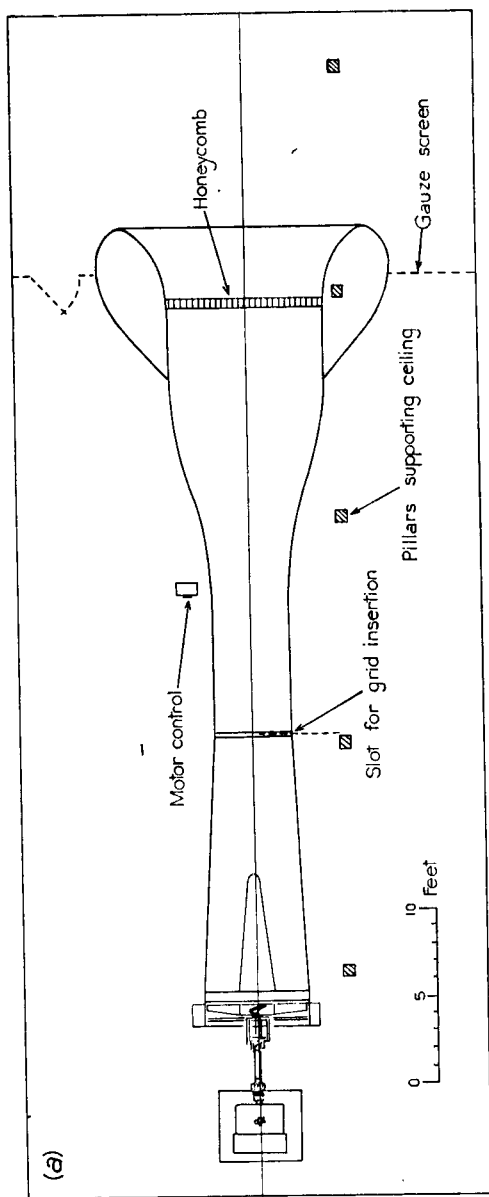


FIGURE 1—WIND-TUNNEL AT BRACKNELL

(a) Plan view
(b) Side elevation

At the fan end of the working section there is a wire guard to catch anything which breaks loose, and a wooden frame into which grids, consisting of plywood sheets with evenly-spaced round holes (Plate IV), can be fixed for obtaining low speeds in the tunnel without getting the uneven flow which results from running the fan very slowly. When the grids are not needed a plywood sheet with an opening $4\frac{1}{2}$ ft by 3 ft is fixed in the frame.

The fan boss is 25 inches in diameter and a tapered fairing is fixed in the centre of the tunnel to lead the air-flow smoothly up and past the fan boss ; the fairing is supported by rods in tension fixed to two of the frames which form part of the tunnel structure.

The entrance to the tunnel (see Plate I) is 9 ft wide by 6 ft high and has a honeycomb wall made of a resin-impregnated paper with a honeycomb structure of $\frac{3}{8}$ -inch mesh supplied in blocks 3 ft by 1 ft by 6 inches thick. This wall is glued in place and is prevented from being drawn into the tunnel by wires across the tunnel on the fan side of the wall.

Beyond the honeycomb and a short rectangular section the tunnel is contracted by suitable smooth curves (see Figure 2) until it is $4\frac{1}{2}$ ft wide by 3 ft high at the beginning of the working section, giving a contraction ratio of 4:1. Four flush suction holes with external connections for piping are made in the walls of the contraction about 3 ft upstream of the working section. The pipes are connected to a common pipe which can be connected to the suction side of a manometer. This pipe can be seen in Plate V behind and in line with the middle of the motor control panel. A pitot-static tube is mounted near the upstream end of the working section, projecting 1 ft into the tunnel at a height of $1\frac{1}{2}$ ft above the floor of the working section. The two outlets from the pitot-static tube are connected to the pressure and suction sides of a sensitive water manometer which can be read to 0.001 inches of water. (See Plate V which shows two such manometers, and the pitot-static tube inside the open door of the working section.)

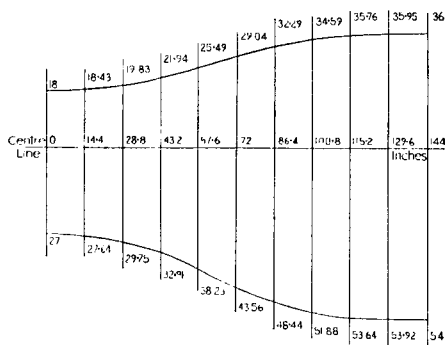


FIGURE 2—DISTANCES FROM CENTRE LINE IN CONTRACTION OF WIND-TUNNEL BEYOND THE HONEYCOMB

The fan is wooden, 6 ft in diameter, 4-bladed, and coupled directly through a short shaft with two universal joints to a 125 h.p. compound wound d.c. electric motor, which at full load takes 219 amps at 460 volts, maximum speed 1440 r.p.m. (Plate III). The power for the motor is supplied from a 400-volt 3-phase a.c. supply by a suitable transformer and mercury-arc

rectifiers. Motor speed control is by a potentiometer knob (Plate V) which can be turned directly, or by means of a worm and wheel to give fine control. This was found to be not quite sensitive enough, and an additional sliding resistance which adjusts the field current of the motor was added to give a finer speed adjustment (see Plate V on the right of the control panel).

To start the tunnel, the rectifier-transformer is first connected to 400-volt a.c. mains. Then the speed control knob is turned as far as it will go anti-clockwise, and the starter button pressed. The speed control knob is then turned clockwise to start the fan, and to increase speed. The slider of the field current control is moved up to increase speed. The manometer (Plate V) is of the type described on pages 255-6 of the 'Handbook of Meteorological Instruments',² but with the sloping-tube indicator replaced by another form of indicator in which the liquid level is adjusted until a pointer near the liquid surface and its reflection appear to meet (or just not to meet, if preferred). This form of indicator is more sensitive than a liquid meniscus in a sloping tube with a fiducial mark. The working section of the tunnel was explored by traversing a pitot-static tube, and the speed distribution is shown in Figure 3.

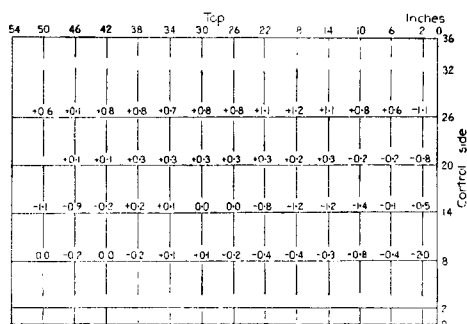


FIGURE 3—DISTRIBUTION OF WIND SPEED AT MIDDLE WORKING SECTION OF WIND-TUNNEL

Figures show percentage differences from mean speed (55.5 ft/s.).

Use of wind-tunnel for anemometer calibration. — As stated in the account of its design, the tunnel is not large enough for absolute calibration of anemometers of normal size. If the projected area of cross-section of the anemometer is an appreciable fraction of the cross-sectional area of the working section, the local speed at the anemometer position will be higher than the mean speed in the working section because the anemometer exercises a blocking effect, whose magnitude cannot easily be determined.

Several standard cup anemometers have therefore been calibrated at NPL in a wind-tunnel large enough (working section 9 ft by 7 ft) for the blockage effect to be neglected ; and one of these anemometers is then placed in the Meteorological Office wind-tunnel and used as a substandard in order to get a relation between wind speed (as obtained from the cup r.p.m.) and tunnel pitot-static pressure. From this a table of manometer readings corresponding to various wind speeds is drawn up, and subsequently these readings are used to set the tunnel speeds when testing other anemometers of the same type. Specimens of generator, counter and contact anemometers have been tested at NPL, and tables of manometer readings prepared for each type.

For smaller anemometers such as hand anemometers, fan air-meters, and small sensitive cup anemometers, direct pitot-static pressure readings are used so that these anemometers can be calibrated absolutely.

Other uses of wind-tunnels.—In conjunction with a smoke generating apparatus the tunnel has been used to explore the wind flow past scale models of various objects, such as the Rock of Gibraltar (aircraft runway wind flow investigation) and the Meteorological Office building, Bracknell (investigation of window breakages under certain wind conditions). Using streamer technique an investigation has been made of the wind flow over Ocean Weather Ships.

It is however possible that these tests are adversely affected by the fact that the wind flow is constrained by the tunnel walls, and probably an open-jet tunnel is more suitable for such work.

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SYNOPTIC DISTURBANCES CAUSING RAINY PERIODS ALONG THE EAST AFRICAN COAST

By F. E. LUMB

Introduction.—In April the Kenya coast (for map of area see Figure 1) partakes of the rainy nature of this month over Kenya as a whole (see Figure 2(a)) but in May when the rainfall inland is decreasing, by contrast on the coast it increases and May is on the average by far the wettest month of the

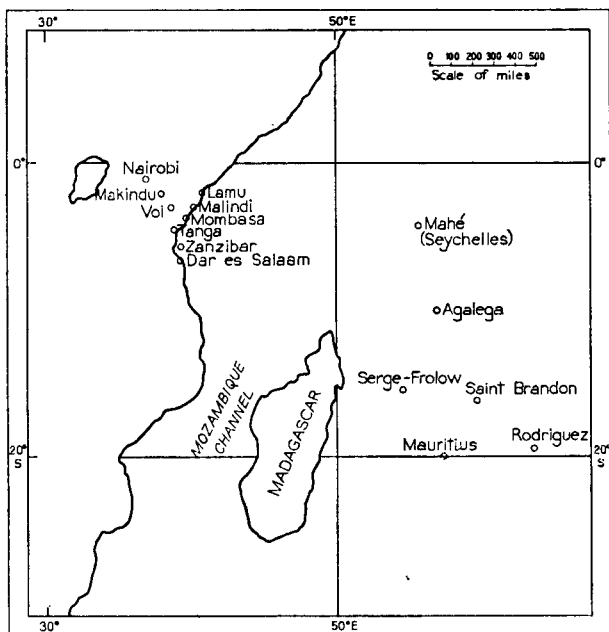
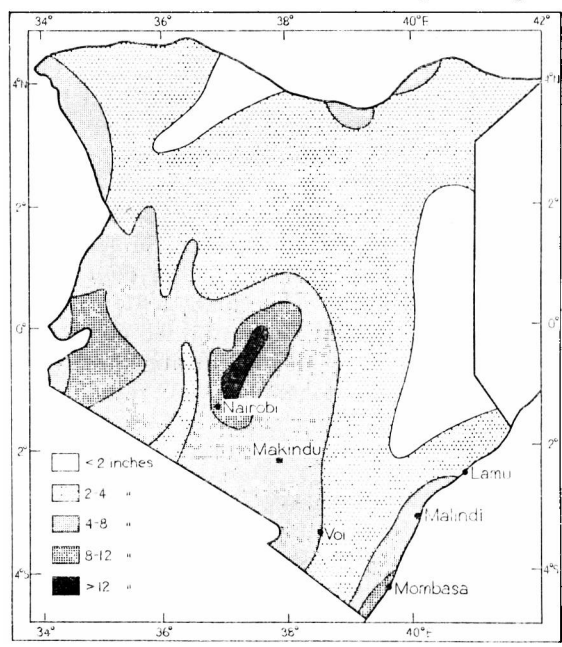
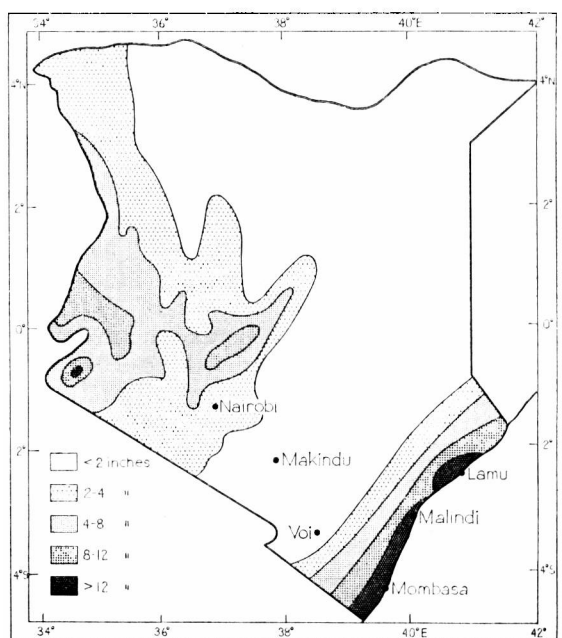


FIGURE 1—MAP OF THE AREA

year, a narrow coastal strip having an average rainfall in excess of 12 inches (see Figure 2(b)). Also during the four months June–September there is a



(a) April



(b) May

FIGURE 2—RAINFALL OVER KENYA

rapid decrease of rainfall from the coast inland, though the rainfall along the coast itself is much less than in May, and decreases from month to month. During the whole of this period the coast of East Africa is under the influence of the south-east monsoon, and the air arriving at the coast has been slowly heated from below during its passage across the Indian Ocean. Hence one might suppose that the coastal belt of high rainfall can be explained by the advection of showers from the Indian Ocean. However, this proves to be an unsatisfactory explanation. A study of the rainfall records from the coastal stations shows that during the months May–September wet spells alternate with dry spells. Showers do occur on many days, but are often only light, and make only a small contribution to the total rainfall. Thus in May 1964 at Malindi measurable rain was recorded on 22 days, with a total fall of 427 mm, but 367 mm (86 per cent of the total) fell during three rainy spells, (7 days altogether). In July 1964 at Lamu rain fell on 16 days, giving a total fall of 155 mm, but 65 per cent of this fell during three rainy spells (4 days altogether). Therefore in order to explain the rainfall at the coast it is necessary to recognize those synoptic disturbances which cause a marked intensification of precipitation over periods of the order of 1 to 2 days.

Basic explanation.—According to Voiron,¹ some of the rainy periods at the East African coast during the months May–September are caused by wave-like perturbations within the easterly current on the north side of the sub tropical high-pressure belt. In the opinion of the author the majority of the rainy periods are associated with the remnants of cold fronts which have intruded into the tropics. Their influence is usually exerted indirectly, confirming the opinion expressed by Forsdyke² that ‘the polar front has little direct significance on moving into the tropics, but it has an indirect significance, in that it may be associated with a surge of cold air which may give rise to convergence and therefore to disturbed weather’.

It is only on the rare occasions when there is an unusually strong incursion of cold air from the south that a cold front can be followed on the surface synoptic charts to the vicinity of the equator. It is more usual for cold fronts to advance west-north-westwards towards the East African coast on the north side of a high cell to the south of Mauritius. (The generalized synoptic maps given by Forsdyke show how this synoptic situation develops.) However, because of the mountainous character of Madagascar, the weak temperature contrast across the northern part of the fronts, and the complete absence of regular observations immediately north and north-west of Madagascar, in many cases it becomes very difficult to position the fronts once their southern part has reached the coast of Madagascar, and their influence on the weather along the coast of East Africa is exerted indirectly, by the generation of a weak ridge of high pressure extending north-north-east from Madagascar. As a concomitant feature a weak trough develops between the East African coast and the Seychelles. See Figure 7 for an example which will be discussed in more detail later. Convergence into the trough, within the convectively unstable air mass, results in the formation of an extensive area of cumulonimbus and altostratus clouds. Probably above the surface trough is a thermal ridge or high, as described by Lockwood,³ but owing to the small changes of height involved, and the absence of upper air data in the immediate vicinity of the trough it is impossible to confirm this.

Once formed, the trough moves slowly towards the coast of East Africa, but it weakens as it approaches the ridge of high pressure which is a permanent feature of the pressure pattern at the surface and 850 mb levels, during the months May to September. The ridge axis lies just inland from the coast at the surface and about 200 miles inland at 850 mb (see surface and 850 mb charts in the atlas 'The climate of Africa'⁴).

Why is the average rainfall along the coast in May much heavier than in the following months? Probably the main factor is that during May the surface equatorial trough is a major synoptic feature over the Indian Ocean just south of the equator, and is sharpened off the Kenya coast by the presence of a surface high over the cold area between the Gulf of Aden and the north-west Arabian Sea. Thus the overall synoptic pattern is favourable for convergence. As the south-west monsoon grows in intensity north of the equator, the trough degenerates into a minor feature, and the surface high is destroyed by the growing cyclonic circulation around the Arabian thermal low (compare sea-level pressure pattern in April and July in the above-mentioned atlas). Also the sea surface temperature is falling gradually from May onwards, so that conditions are more favourable for vigorous convection in May than in the following months.

In the remainder of this article, three synoptic examples will be presented. The first is an example of the rather rare case of a cold front having a direct influence on the weather along the East African coast. The second and third (one straightforward, the other more difficult) illustrate the more usual state of affairs when the influence of the cold front is exerted indirectly.

Example of cold front penetrating to the vicinity of the equator.—

Figure 3 shows the synoptic situation at 0600 GMT on 2 June 1965. The low

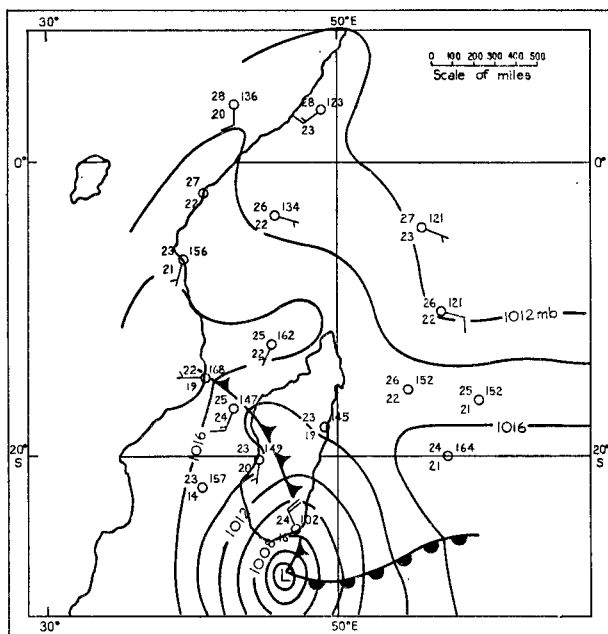


FIGURE 3—SYNOPTIC SITUATION AT 0600 GMT ON 2 JUNE 1965

In Figures 3, 4, 6, 7 and 9, temperature, dew-point, pressure and wind are plotted in the conventional manner and in Figures 7 and 9 24-hour pressure tendencies are included.

just to the south of Madagascar deepened rapidly during the next 48 hours and moved slowly east-south-east. By 0600 GMT on 4 June (see Figure 4) cold air has clearly penetrated right through the Mozambique Channel. The approximate position of the cold front is as shown in Figure 4 ; its passage was marked by a thunderstorm at Lamu. There was a large surge of pressure behind the cold front, the 1018 mb isobar having advanced with it.

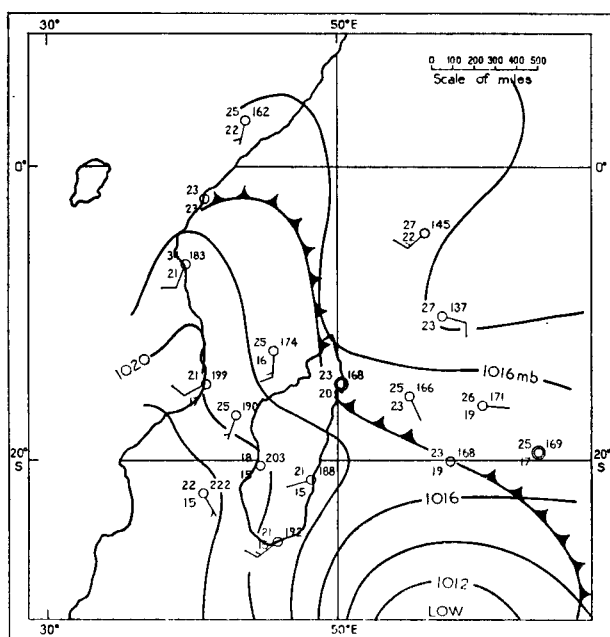


FIGURE 4—SYNOPTIC SITUATION AT 0600 GMT ON 4 JUNE 1965
Note: the temperature at Dar es Salaam should read 24°C.

The difference between the two air masses is revealed by comparing the Dar es Salaam tephigrams of 1200 GMT on 3 and 5 June (see Figure 5). The dry-bulb and dew-point temperatures fell at all heights up to 750 mb.

Rainfall amounts associated with the cold front were much larger in the north than in the south (e.g. 56 mm at Lamu, 14 at Mombasa, 1 at Dar es Salaam). This is probably explained by the fact that the predominantly southerly winds (up to 700 mb) in which the front was embedded have a rapidly increasing fetch over the sea northwards of Mombasa.

A straightforward example of trough development due to the approach of colder air.—A fairly straightforward example of trough development caused by the approach of a cold front resulted in a rainy spell on the Kenya coast on 26, 27 and 28 May 1965. At 0600 GMT on 24 May (see Figure 6) colder air has passed Saint Brandon and Mauritius and is moving west-north-west (dew-points have fallen 6°C at Saint Brandon and 3°C at Mauritius since 0600 GMT on the 23rd). By 0600 GMT on the 25th (see Figure 7) the colder air has passed Serge-Frolow and Agalega and has probably reached the Seychelles. However, the precise position of the cold front is of less importance for events on the East African coast than the effect

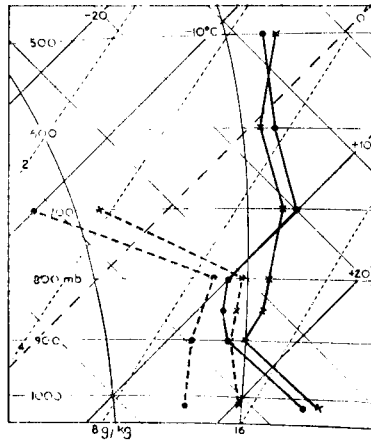


FIGURE 5—UPPER AIR ASCENT AT DAR ES SALAAM AT 1200 GMT ON 3 AND 5 JUNE 1965

1200 GMT, 3 June 1965
 x—x Dry-bulb temperature
 x—x Dew-point

1200 GMT, 5 June 1965
 ···· Dry-bulb temperature
 ···· Dew-point

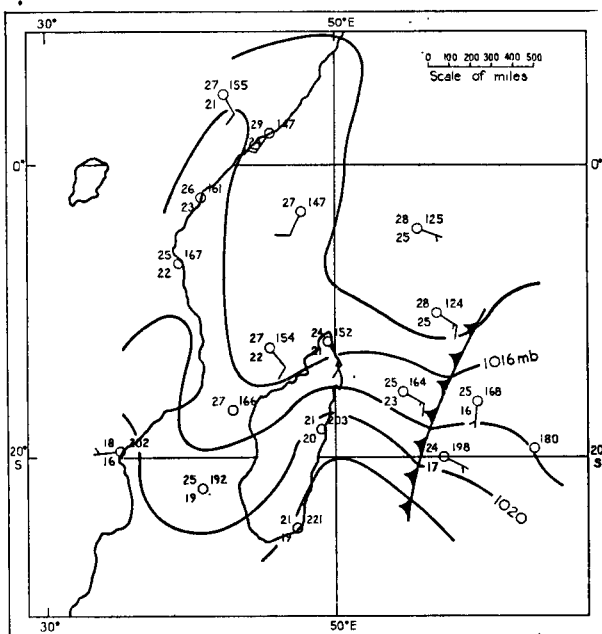


FIGURE 6—SYNOPTIC SITUATION AT 0600 GMT ON 24 MAY 1965

on the surface pressure field of the advance of the colder air from the east-south-east. Comparing Figures 6 and 7, it can be seen that the effect is to build over the east coast of Madagascar a ridge which extends northwards to about latitude 5°S (note the isallobars in Figure 7). Downstream the ship's report at 09.1°S , 44.6°E (see Figure 7) confirms that a trough has developed between the East African coast and the Seychelles.

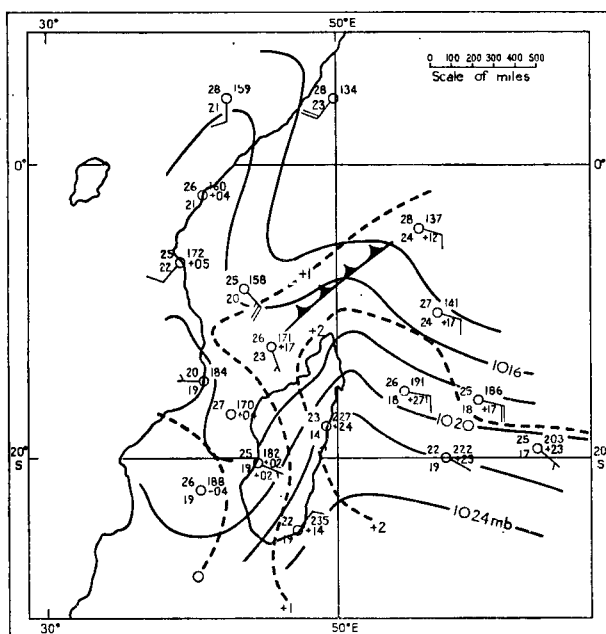


FIGURE 7—SYNOPTIC SITUATION AT 0600 GMT ON 25 MAY 1965

--- Isallobars at intervals of 1 mb (for 24 hours)

It is interesting to compare the winds up to 400 mb at Dar es Salaam at 1200 GMT on 25th and 26th (see Table I).

TABLE I—SURFACE AND UPPER WINDS AT DAR ES SALAAM, 25–26 MAY 1965

Date	Surface	900mb	850mb	800mb	700mb	600mb	500mb	400mb
					<i>degrees/knots</i>			
25 May 1965	160/13	163/13	163/12	163/18	151/09	259/11	022/14	019/09
26 May 1965	130/07	112/21	112/21	109/21	121/18	103/12	085/12	067/06

With some strengthening of the subtropical high-pressure belt (at 700 mb) extending east-west approximately along latitude 20°S, easterly winds with very little shear had become established between 900 and 500 mb by 1200 GMT on the 26th.

The sequence of events leading to rain at the coast therefore probably was as follows : between 24 and 25 May a low-level trough developed between the East African coast and the Seychelles ; convergence into the trough resulted in an extensive area of cumulonimbus and altostratus clouds ; and between the 25th and 26th the winds between 900 and 500 mb became generally easterly, and carried the rain-bearing clouds westward to the coast.

Rain reached the coast early on the 26th and spread inland as far as Nairobi during the next 24 hours, but as usual in this type of situation, the amounts of rain decreased rapidly inland from the Kenya coast, e.g. up to 0600 GMT 28 May the following amounts were reported :

Mombasa	75 mm	Voi	52 mm
Makindu	16 mm	Nairobi	2 mm

It is at first sight surprising that the rainfall should decrease so quickly inland, especially since the westward flowing air is subject to orographic uplift of some 2000 metres until reaching the Rift Valley (about 300 miles inland). However the orographic effect is counteracted by divergence and

subsidence in the lower troposphere associated with the ridge of high pressure which has already been mentioned as being a permanent feature of the pressure pattern at the surface and at 850 mb inland from the coast during the months May to September. Along and near the coast the rainfall is probably greatly augmented by convection within the rain-cooled air. Figure 8 is the upper air temperature sounding for Dar es Salaam at 1200 GMT on 28 May at the end of the rainy spell. The sounding indicates that the main cloud mass extended up to 500 mb but bearing in mind that the sea temperature off the coast was around 29°C it is clear that cumulonimbus clouds could develop with tops up to at least 400 mb.

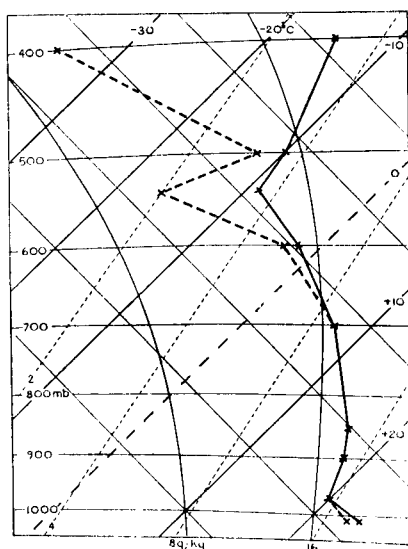


FIGURE 8—UPPER AIR ASCENT AT DAR ES SALAAM AT 1200 GMT ON 28 MAY 1965

x — x Dry-bulb temperature
x - - x Dew-point

A difficult example of trough development due to the approach of colder air.—A less clear-cut example gave the heavy rains on the coast of Kenya during 27 and 28 May 1964. (During the 48 hours ending 0600 GMT, 28 May, Mombasa recorded 95 mm and Lamu 25.) Figure 9 shows the synoptic chart for 0600 GMT, 25 May 1964. The essential features are the same as for 0600 GMT, 25 May 1965 (see Figure 7) but less well marked. Somewhat colder air has advanced west-north-west between Madagascar and the Seychelles, but has given only small falls of dew-point (1°C at Mahé, no change at Agalega, and 2°C at Serge-Frolow and Saint Brandon during the last 24 hours). As revealed by the 24-hour isallobars, there has been some ridge development from north Madagascar to the Seychelles, and also along the coast of Tanzania. (The latter was probably associated with a surge of pressure over a wide area to the south, as a vigorous cold front away to the south was followed by an intensifying anticyclone, which at 0600 GMT 26 May was centred at 35°S, 32°E.)

Trough development between the coast and the Seychelles can be expected as a consequence of the rising pressure tendencies on either side. The ship

at 04.5°S, 46.2°E (see Figure 9) gave a surface wind of 200° 18 knots and reported rain in sight and thick layers of medium cloud. This combination of wind, weather and cloud is strong evidence for the existence of a developing trough to the south-east of the ship. Rain started at the coast on the morning of the 27th, and lasted until almost midday on the 28th.

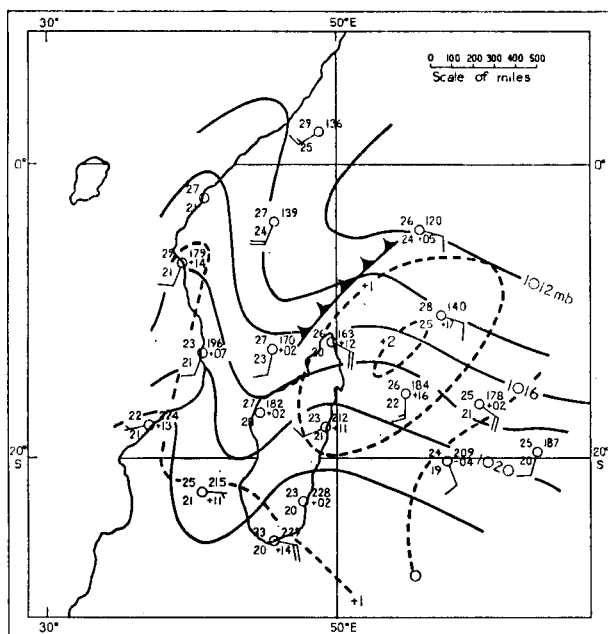


FIGURE 9—SYNOPTIC SITUATION AT 0600 GMT ON 26 MAY 1965
 - - - - Isallobars at intervals of 1 mb (for 24 hours)

It is interesting to examine the upper winds at Dar es Salaam at 1200 GMT on 27 and 28 May 1964 (see Table II) and to compare them with those for the May 1965 example already considered.

TABLE II—SURFACE AND UPPER WINDS AT DAR ES SALAAM, 27-28 MAY 1964

Date	Surface	900mb	850mb	800mb	700mb	600mb	500mb	400mb
				<i>degrees/knots</i>				
27 May 1964	181/12	175/26	166/29	160/33	109/21	109/21	088/12	015/16
28 May 1964	160/13	160/23	163/24	133/18	097/18	097/18	028/06	307/14

It is seen from Table II that the winds up to 800 mb retained a large southerly component, easterly winds being established only from 700 mb upwards. This resulted in a change in the distribution of the rainfall as compared with May 1965. Only cloud at 700 mb and above was advected westwards inland so that the rainfall inland was less than in May 1965. Voi reported only 1 mm (as compared with 52 mm in 1965) and Makindu only 2 mm (as compared with 16).

The need for cloud photographs from satellites.—These examples clearly illustrate the difficulty in forecasting rainy periods along the coast of East Africa. The surface troughs are small-scale features on a synoptic scale, and some are initiated by the approach of weak cold fronts which are

very difficult to detect from surface synoptic reports. On occasions when the development of a trough is suspected, it is a matter of chance whether a ship reports in the right place and at the right time to give direct evidence of the trough's existence.

The regular receipt of cloud photographs over the Indian Ocean from meteorological satellites by automatic picture transmission (APT) should greatly facilitate the forecasting of the onset of rainy spells along the coast of East Africa. The East African Meteorological Department has already constructed and installed APT receiving equipment, so as to make full use of the APT facilities of the operational satellite system.

Acknowledgement.—The author wishes to thank Mr. B. W. Thompson and Dr. H. W. Sansom for their very helpful comments. This paper is published by permission of the Director of the East African Meteorological Department.

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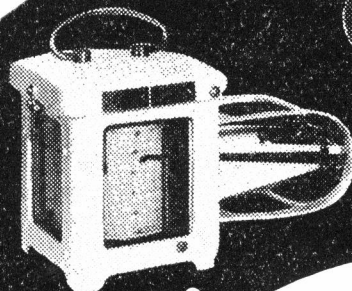
REVIEW

Cloud physics and cloud seeding by Louis J. Battan. $4\frac{3}{4}$ in \times $7\frac{1}{2}$ in, pp. xii + 144, illus., Heinemann Educational Books Ltd., 48 Charles St., London, W1. Price : 12s. 6d.

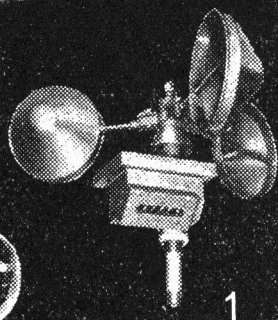
Books in the Science Study Series are intended to provide a survey of a particular field in physics and to put it within the grasp of the school physics student and the layman. This book in the series covers the physics of water droplets and ice crystals and the processes they undergo in clouds. First there is a discussion of the beginnings of condensation on nuclei and the subsequent growth of cloud particles into rain, snow and hail. In later chapters Dr. Battan discusses the scientific basis of attempts to modify clouds, stimulate rainfall and interfere with hailstorms.

In covering his subject simply Dr. Battan has mostly managed to avoid misleading over-generalizations. This is probably least true in places where the micro-physics of cloud particles is related to larger-scale meteorology and the laymen for whom the book is intended would do well to read a simple, modern, meteorological text first. They would not then, for example, be led astray by the cross-sections through a warm front and Ludlam's model of a severe storm, which make both systems appear the size of an ordinary shower. In the whole book, however, there are only a few matters of fact one would wish to question and while it lacks the authority of a textbook, this little book succeeds in being the most easily read, reasonably comprehensive, book on cloud physics now available. It can be recommended as interesting reading for those for whom it was intended and for meteorological observers. It is well produced.

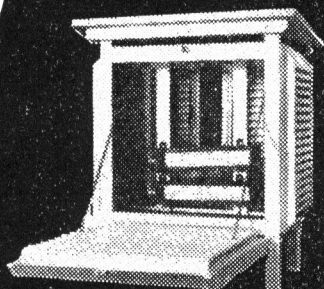
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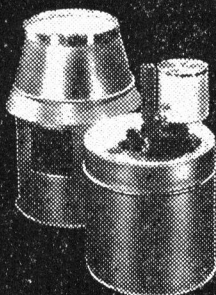
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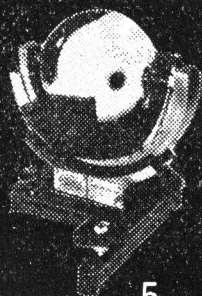
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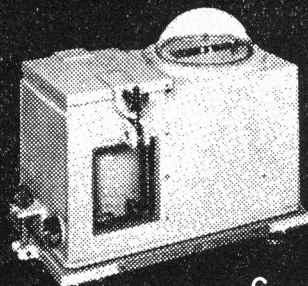
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