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SCIENTIFIC PAPERS

No. 31 The three-dimensional analysis of meteorological data

By R. Dixon, B.Sc. and E. A. Spackman, M.Sc.

The advent of modern observational devices such as satellites and long-life free drifting balloons has greatly complicated the process of data analysis by computer. This paper presents a possible method for effecting this data analysis by fitting a high-power polynomial to all the observations from within a large volume of the atmosphere.

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By G. R. R. Benwell, M.A., A. J. Gadd, Ph.D., J. F. Keers, B.Sc., Margaret S. Timpson, B.Sc., and P. W. White, Ph.D.

A full description is given of the 10-level numerical weather prediction model which has been developed by the Meteorological Office during the past few years for use in investigating the dynamics of fronts and in predicting rainfall. The formulation includes representation of the effects of surface friction, topography surface exchanges of sensible and latent heat, sub-grid-scale convection, and lateral diffusion. An example of a recently computed forecast is included.

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ERRORS IN 48-HOUR MOVEMENT AND DEVELOPMENT OF COMPUTER-FORECAST 500-MILLIBAR TROUGHS AND RIDGES: AMERICAN AND BRITISH MODELS COMPARED

By M. J. DUTTON

Summary. Although it is known that computer-forecast troughs and ridges suffer generally from slowness in west-to-east translation, very little quantitative work has been done on this subject. This paper summarizes some of the results of an analysis of errors in movement and development of 48-hour forecast 500-mb troughs and ridges (at 50°N from 110°W to 40°E) as forecast by the British 3-level 'vorticity' model (at the Meteorological Office, Bracknell) and the American 6-level primitive equation (PE) model (at the National Meteorological Center, Washington). The period of the analysis was June to November 1970.

Although the results reveal that there is little apparent significant difference in performance between the two models, the movement-error statistics do indicate a slight overall superiority of the 6-level PE model, more particularly over the North American and European continents. Differential biasing of the development errors by a mode of error dependent on the efficiency of the surface modelling obscures the issue in any direct comparison of the mean development errors, but by introducing a 'developmental efficiency' term, which is independent of the biasing, it can be shown that here again, the 6-level PE model is superior.

Glossary of symbols used and definitions.

Subscript T is used to refer to trough parameters.

Subscript R is used to refer to ridge parameters.

x = Horizontal west-to-east co-ordinate.

L = Longitude.

M = 48-h movement of trough/ridge axis at 50°N.

D = 48-h development in trough/ridge axis at 50°N (defined as the change in contour height at trough/ridge axis).

E_{ij} = Grid-point contour-height error (forecast minus observed contour height).

$(E_{ij})_s$ = Stationary mode component of E_{ij}.

E_m = Error in 48-h movement of trough/ridge axis at 50°N.

E_d = Error in 48-h development of trough/ridge axis at 50°N.

Δ = Development efficiency. $\Delta = \overline{E_d}(\text{AM}) - \overline{E_d}(\text{RE})$, where $\overline{E_d}(\text{AM})$ is mean development-error for amplifying systems and $\overline{E_d}(\text{RE})$ is mean development-error for relaxing systems.

$\overline{E_m}$, $\overline{E_d}$ etc. represent time-meaned quantities (usually 6-monthly means).

σ_m = Standard deviation of movement error.

MET = Abbreviation used to refer to the British 3-level model.

NMC = Abbreviation used to refer to the American 6- level model.

Introduction. Over the past 15 to 20 years, results of numerous investigations concerning verification of forecasts made by numerical weather prediction (NWP) models have clearly indicated that in all the models forecast troughs and ridges suffer typically from three main defects :

(a) *Slowness in evolution.* This defect is particularly evident in forecasts of 48 hours or more in situations where a local change from high to low zonal index (or vice versa) takes place. In such situations the numerical model will usually forecast adequately the change in type but will just as usually underestimate the rate of change of type.

(b) *Slowness in west-to-east translation.* In general the greater the phase speed of the system the 'slower' the numerical forecast (trough and ridge axes are moved eastward too slowly in the forecast). Slow-moving features or, more particularly, long-wave large-amplitude features do not normally suffer from this defect; in many cases the phase speed of such systems is overforecast.

(c) *Lack of amplitude.* This feature, which is more often associated with amplifying systems, is usually a direct consequence of the slowness in evolution ((a) above); the greater the rate of amplification the greater the amplitude error.

Mainly because of the largely subjective nature of the work involved, little has been done in the past to investigate quantitatively the slowness in eastward translation of individual forecast troughs and ridges. The majority of NWP verification reports have been restricted to the examination of monthly or seasonally meaned contour-height-error charts at various levels. Although useful in the diagnosis and (only occasionally) subsequent correction of some systematic errors, such investigations often prove to be of limited direct use to the human forecaster in his interpretation and modification of the daily computer product.

This report is mainly concerned with the errors in eastward translation (at 50°N latitude) of individual 48-hour forecast 500-mb troughs and ridges as computed by the British (Meteorological Office, Bracknell) and American (National Meteorological Center, Washington) operational NWP models. The British model is a 3-level 'filtered' vorticity model (Bushby and Whitelam[1]) and the American model is a 6-level primitive-equation model (Shuman and Hovermale[2]).

An investigation of errors in development of individual troughs and ridges is incorporated in this report which summarizes some of the results obtained over a period of 6 months from June to November 1970.

Summary of some previous verification results. The majority of verification reports on these two NWP models have been concerned mainly with subjective examination of monthly or seasonally meaned contour-height-error charts of which Figures 1 (a)–(d) are examples. They show mean observed 500-mb contour height and the associated mean 48-h prognostic error in the British 3-level (referred to as MET in this report) and the American 6-level (referred to as NMC) models for January and July of 1968. Seasonal variations in such error fields can be considerable, but certain features stand

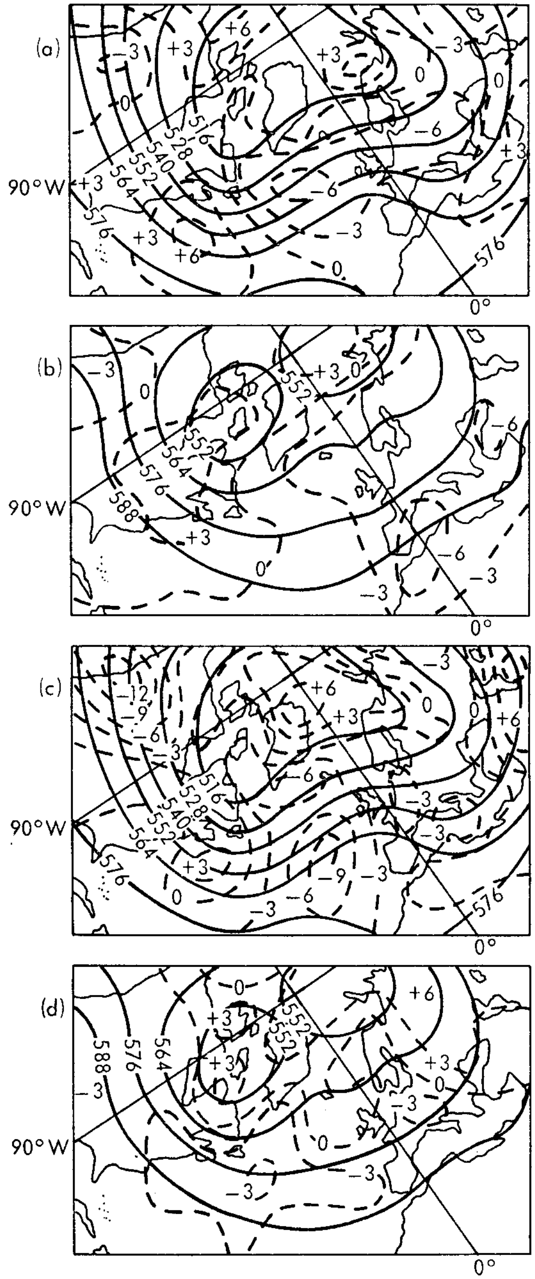

FIGURE 1—MEAN OBSERVED 500-MILLIBAR CONTOUR HEIGHT AND 48-HOUR PROGNOSTIC MEAN 500-MILLIBAR CONTOUR-HEIGHT ERROR

(a) Three-level (MET), January 1968. (b) Three-level (MET), July 1968.
(c) Six-level (NMC), January 1968. (d) Six-level (NMC), July 1968.
[(a) and (b) after R. M. Morris, 1970, (c) and (d) after J. F. Andrews.[4]]
Heights are in decametres. Error is forecast minus observed contour-height, in decametres.

out under subjective examination (Fawcett,[3] Andrews,[4] and an unpublished paper by R. M. Morris).

Basically the error fields can be regarded as a superposition of a number of modes of error. A stationary mode, $(\overline{E_{ij}})_S$, determined by the efficiency of the modelling at or near the surface boundary, is usually discernible by its apparent association with continental-scale variation in the nature of the surface boundary. Particular examples of this mode of error can be found by examination of a series of 48-h 500-mb mean-height-error charts; they can be recognized as features which are apparently independent of the local mean circulation type and appear to be solely dependent on the large-scale nature of the surface boundary. Similarly a non-stationary mode of error dependent on the local mean circulation type can be recognized; in 48-h forecasts (at 500 mb) negative contour-height errors tend to persist in mean ridges while positive errors dominate mean troughs (contour-height error is defined as the forecast minus the observed contour height). This circulation-dependent mode of error is usually more evident in MET than in NMC. In the latter the positive error associated with mean troughs tends to be situated farther to the north than it is in MET, usually to the north of the mean jet-stream, and in many cases negative error dominates the base of the mean trough. The magnitude of this type of error is normally simply dependent on the amplitude of the corresponding mean trough/ridge system; the greater the amplitude the greater is the magnitude of the error. In both MET and NMC much of the North Atlantic is dominated by negative stationary-mode error (which is normally considerably accentuated by the negative non-stationary-mode error associated with the existence of a local mean ridge). In MET this area of negative error extends eastward, increasing in magnitude to dominate the European continent and much of the Mediterranean. The magnitude of this type of error is normally greatest over the winter months and smallest over the summer months.

In some cases, where mean circulation types are strongly allied to particular areas at certain seasons of the year (so-called 'anchored' features) it is difficult to determine to what extent either of these two main modes of mean error is dominant. One classic example of such a case is the large area of positive contour-height error associated with the Canadian trough over the winter months (the areal extent and amplitude of this positive error in the Canadian trough are invariably substantially greater in MET than in NMC). In isolated areas adjustment to the modelling at and near the surface boundary can significantly reduce, if not eliminate entirely, the magnitude of the stationary-mode error; in September 1968 substantial adjustments to the modelling of the Rocky Mountains in NMC led to the virtual elimination of a large area of negative error which had previously dominated western Canada (Fawcett[3]).

The main limitation of this type of subjective examination of monthly meaned error fields is that it can give no indication of errors in movement or in amplitude of individual troughs and ridges. Hence, in addition to an investigation of movement errors, this report incorporates an analysis of development (or amplitude) errors in individual 48-h forecast troughs and ridges at 50°N (at the 500-mb level).

The data and analysis. The trough and ridge movement and development data (observed and forecast) were extracted from the following charts :

(a) 00 GMT 1:30 million 500-mb analysis (subjective, Central Forecasting Office, Bracknell),

(b) 00 GMT 1:30 million 500-mb 48-h forecast (MET),

(c) 00 GMT 1:30 million 500-mb 48-h forecast (NMC).

From June to November 1970, current data were collected for all wavelengths of troughs and ridges, except for very short-wavelength, low-amplitude, non-amplifying systems.

The position of a trough or ridge was taken as the point of intersection of its axis and the 50°N latitude circle; the contour height associated with the trough or ridge was taken as the contour height at this point. The observed 48-h movement, M, (to the nearest whole degree of longitude) and development, D, (to the nearest whole decametre) of troughs and ridges, and the corresponding movement and development errors, E_m and E_d, in the NWP models' forecast systems, are then directly obtainable.

The analysis was divided areally into three parts :

(a) area A 110°W–50°W (Rockies to Newfoundland)

(b) area B 50°W–00° (North Atlantic)

(c) area C 00° –40°E (western and central Europe).

The movement-error statistics were categorized in terms of the observed 48-h movement, M, of individual troughs and ridges. The five categories of M are :

(a) $M \leqslant 9$°L (including retrogressive systems)

(b) $10 \leqslant M \leqslant 19$°L

(c) $20 \leqslant M \leqslant 29$°L

(d) $30 \leqslant M \leqslant 39$°L

(e) $M \geqslant 40$°L.

Mean values of E_m and corresponding standard deviations, σ_m, are given for each M category (for each of the three areas) (Tables I, II, III and Figure 2(a), (b) and (c)). Table IV, showing movement-error frequencies, gives for the three areas A, B and C the percentages of troughs and ridges (of all values of M) with :

(a) $|E_m| < 5$°L (forecast movement correct to within 4°L)

(b) $E_m \leqslant -5$°L (forecast movement more than 4°L 'slow')

(c) $E_m \leqslant -11$°L (forecast movement more than 10°L 'slow')

(d) $E_m \geqslant +5$°L (forecast movement more than 4°L 'fast').

Development-error statistics for each of the three areas are subdivided into two main categories :

(a) Amplifying systems (AM)

(b) Relaxing systems (RE)
(Tables V, VI, VII).

Results are also given for the combination of all areas (Tables VIII, IX and Figure 2(d)).

In all the tables and figures the British 3-level vorticity model is referred to as MET, and the American 6-level PE model as NMC. These abbreviations are arbitrary and are used for ease of reference, they bear no other significance.

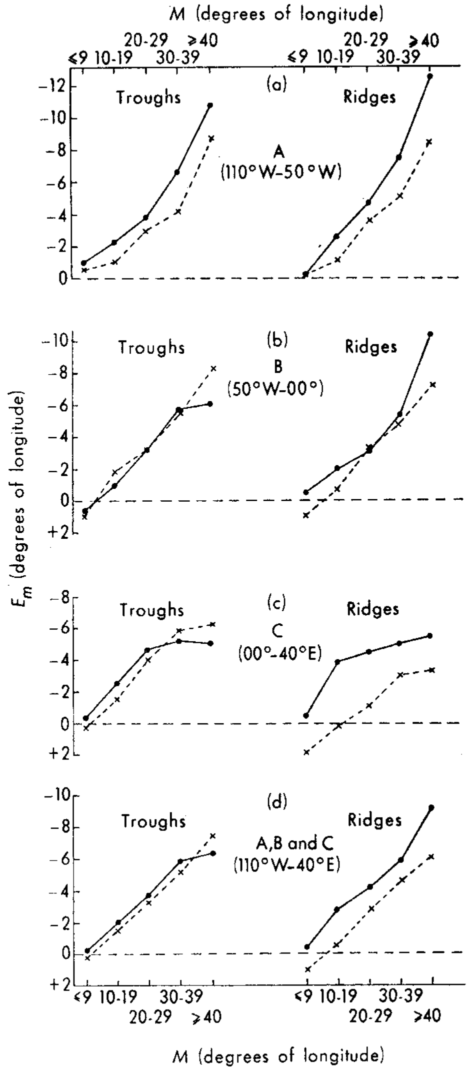

FIGURE 2—MEAN 48-HOUR MOVEMENT ERRORS, JUNE–NOVEMBER 1970

●——● British three-level model (MET). x – – – x American six-level model (NMC).

General discussion of results. The results for each area will be discussed separately but initially it may be useful to indicate in general terms the type and magnitude of movement and development errors that existed over the entire area of this analysis (110°W to 40°E).

The analysis confirmed that, in general, the greater the observed phase speed of the system, the 'slower' the corresponding forecast system (Tables VIII and IX and Figure 2(d)). For both MET and NMC models, mean movement-errors for forecast troughs vary from about 0°L (standard deviation $\approx$4°L) for the slowest-moving systems ($M_T \leqslant 9$°L) to about 10°L (standard deviation $\approx$7°L) for the fastest systems ($M_T \geqslant 40$°L). For ridges, mean movement-errors vary similarly with phase speed but NMC forecast ridges tend to be significantly less slow than corresponding MET ridges. The movement-error frequencies (Table IV) also indicate that, for trough movement, there is no significant difference between MET and NMC mean performance from 110°W to 40°E; for ridge movement the difference between MET and NMC is reflected in the percentages of ridges more than 4°L slow — these are 34 per cent for MET and significantly less, 23 per cent, for NMC.

Although the mean development-error statistics may serve as a general guide in any modification of the models' forecasts, useful discussion of these results is limited, particularly in a general context, by the biasing effect of the stationary-mode component of $\overline{E_{ij}}$ (i.e. $(\overline{E_{ij}})_s$) described earlier, especially since these $(\overline{E_{ij}})_s$ fields are not easily determinable. Rough estimates of the $(\overline{E_{ij}})_s$ values applicable to each area over the period June–November 1970 can be determined from the mean development-errors. These are :

	Area A	Area B	Area C
		decametres	
MET	+3·0	−1·5	−3·5
NMC	−1·0	−2·5	+0·5

One obvious general conclusion which can be drawn from the mean development-errors is that, in both models, amplifying troughs and relaxing ridges contain positive error (contour height overforecast) while relaxing troughs and amplifying ridges contain negative error (contour height underforecast).

As a simple method of bypassing the difficulty of not having more precise values of $(\overline{E_{ij}})_s$, the quantity Δ is introduced here as a measure of 'developmental efficiency' and is defined as :

$$\Delta = \overline{E_d}\,(\text{AM}) - \overline{E_d}\,(\text{RE})\ ,$$

where $\overline{E_d}$ (AM) is the mean development-error for amplifying systems and $\overline{E_d}$ (RE) is that for relaxing systems. Δ is considered a reasonable measure of developmental efficiency since it is independent of the biasing effect of the $(\overline{E_{ij}})_s$ fields. If this stationary mode of error was the only one present in the models, then at any one position along 50°N both amplifying and relaxing systems would contain the same sign and magnitude of mean error (namely the mean stationary-mode error associated with that position) and Δ would be zero. In reality, however, the stationary-mode component is obviously not the only component of $\overline{E_{ij}}$; as already pointed out, positive error tends to occur in amplifying troughs and relaxing ridges and negative error in relaxing troughs and amplifying ridges. Δ is therefore invariably positive for troughs and negative for ridges, and the greater the magnitude of Δ the less efficient (developmentally) is the model. Table X lists values of Δ for each area; these figures are derived directly from values of $\overline{E_d}$ in Tables V, VI, VII and IX.

For the three areas A, B and C taken as a whole the values of Δ indicate an overall superiority of NMC in the handling of both trough and ridge development (i.e. development as defined in this context).

It is worth pointing out at this stage that just as the development-error statistics are biased by $(\overline{E_{ij}})_s$, so the movement-error statistics are subject to

TABLE I—MOVEMENT ERRORS, E_m, FOR AREA A (110°W–50°W), JUNE–NOVEMBER 1970

	M	MET $\overline{E_m}$	MET σ_m	NMC $\overline{E_m}$	NMC σ_m	Number sampled
		degrees of longitude				
Troughs	⩽9	−1·0	3·6	−0·5	3·8	33
	10–19	−2·3	4·1	−1·0	4·2	61
	20–29	−3·8	4·3	−3·0	3·4	46
	30–39	−6·7	6·6	−4·2	5·6	19
	⩾40	−10·8	*	−8·5	*	4
Ridges	⩽9	−0·2	4·2	−0·2	3·9	41
	10–19	−2·6	5·3	−1·1	4·6	49
	20–29	−4·7	4·6	−3·4	3·6	44
	30–39	−7·5	2·8	−5·0	2·9	12
	⩾40	−12·5	*	−8·5	*	4

* Sample too small for standard deviation to be significant.

An explanation of the symbols is given in the glossary.

TABLE II—MOVEMENT ERRORS, E_m, FOR AREA B (50°W–00°), JUNE–NOVEMBER 1970

	M	MET $\overline{E_m}$	MET σ_m	NMC $\overline{E_m}$	NMC σ_m	Number sampled
		degrees of longitude				
Troughs	⩽9	+0·6	4·0	+0·9	3·6	48
	10–19	−1·1	3·9	−1·9	3·6	39
	20–29	−3·2	3·4	−3·2	3·5	42
	30–39	−5·8	4·3	−5·4	5·9	31
	⩾40	−6·1	7·7	−8·1	9·1	20
Ridges	⩽9	−0·5	4·2	+1·0	3·8	52
	10–19	−2·0	3·6	−0·7	3·6	48
	20–29	−3·0	3·0	−3·1	4·3	36
	30–39	−5·4	6·2	−4·8	5·3	25
	⩾40	−10·5	*	−7·2	*	6

* Sample too small for standard deviation to be significant.

An explanation of the symbols is given in the glossary.

TABLE III—MOVEMENT ERRORS, E_m, FOR AREA C (00°–40°E), JUNE–NOVEMBER 1970

	M	MET $\overline{E_m}$	MET σ_m	NMC $\overline{E_m}$	NMC σ_m	Number sampled
		degrees of longitude				
Troughs	⩽9	−0·4	3·1	+0·1	3·9	53
	10–19	−2·5	3·0	−1·7	4·0	42
	20–29	−4·7	3·7	−4·1	3·6	28
	30–39	−5·2	4·5	−5·8	3·8	14
	⩾40	−5·0	2·9	−6·2	4·2	12
Ridges	⩽9	−0·5	3·3	+1·9	3·4	63
	10–19	−3·9	3·5	+0·2	3·7	40
	20–29	−4·5	3·4	−1·0	3·8	24
	30–39	−5·0	*	−2·9	*	9
	⩾40	−5·7	*	−3·3	*	6

* Sample too small for standard deviation to be significant.

An explanation of the symbols is given in the glossary.

bias by $\partial(\overline{E_{ij}})_s/\partial x$, the west-to-east gradient of the mean stationary-mode error along the 50°N latitude circle. If, for instance, a positive west-to-east gradient of $(\overline{E_{ij}})_s$ exists locally, axes of forecast troughs would be systematically displaced westwards and those of forecast ridges eastwards. Amounts by which the axes are displaced are normally insignificant for the majority of troughs and ridges and this aspect is discussed in a little more detail in the discussion of results for area C, where this effect is most marked.

Results for area A (110°W–50°W). Differences in performance between MET and NMC were more consistently marked in this area over the North American continent (at 50°N) than in either of the other two areas, B and C. Better handling (movement *and* development) of troughs and ridges by NMC was usually the case.

(a) *Movement errors* (Table I and Figure 2(a)). Although NMC mean movement-errors were consistently smaller in magnitude than those of MET, the most significant differences arose for systems with $M \geqslant 30$°L (mainly short-wave systems). By consideration of systems over the entire range of phase speeds, Table IV shows, for instance, that the percentage of forecast troughs which were more than 10°L slow (i.e. $E_m \leqslant -11$°L) was 2 for NMC and 9 for MET; the corresponding figures for ridges were 3 (NMC) and 8 (MET). The performance of MET in this area was noticeably worse than its performance in either of the other two areas; the opposite is true for the NMC, its performance here being slightly better than in the other areas.

(b) *Development errors* (Table V). Area A development errors in MET are positively biased by the extensive area of positive $(\overline{E_{ij}})_s$ usually associated with much of the North American continent downwind of the Rockies; in NMC the corresponding mean biasing-error is usually negative but of negligible magnitude. Values of the developmental efficiency, Δ (Table X), for this area indicate a marked superiority of NMC for both trough and ridge development.

Certain aspects of the superiority of NMC over MET in this area can probably be attributed to effects arising from the closer proximity of the western and southern lateral boundaries of the forecast area in MET and the greater efficiency of the Rockies modelling in NMC.

Results for area B (50°W–00°). In this area over the North Atlantic there were few significant differences in performance between the two models.

(a) *Movement errors* (Table II and Figure 2(b)). From the statistics obtained over this 6-month period MET forecasts appear to have had a slight edge over NMC forecasts for trough movement; for ridge movement this situation was reversed, NMC being slightly the better. It is interesting to note that the slowest-moving troughs (usually long-wave systems) have positive mean movement-error in both models' forecasts (i.e. forecast troughs 'fast').

The movement-error frequencies in Table IV illustrate the degree of similarity in the performance of the two models; the percentage of all forecast troughs with movement error more than 4°L slow (i.e.

TABLE IV—MOVEMENT-ERROR FREQUENCIES FOR THE THREE AREAS, JUNE–NOVEMBER 1970

Troughs/ridges with :			Area A (110°W–50°W)	Area B (50°W–00°)	Area C (00°–40°E)	All three areas
				per cent		
$\|E_m\| < 5°L$	Troughs	MET	64	63	70	65·5
		NMC	67	63	65	65
	Ridges	MET	50	59	71	60
		NMC	60	66	74	67
$E_m \leqslant -5°L$ ('slow')	Troughs	MET	32	30	27	29·5
		NMC	27	31	31	29·5
	Ridges	MET	43	34	25	34
		NMC	30	26	13	23
$E_m \leqslant -11°L$ ('very slow')	Troughs	MET	9	7	1·5	6
		NMC	2	9	3	5
	Ridges	MET	8	4	2	4·5
		NMC	3	3	nil	2
$E_m \geqslant +5°L$ ('fast')	Troughs	MET	4	7	3	5
		NMC	6	6	4	5·5
	Ridges	MET	7	7	4	6
		NMC	10	8	13	10

TABLE V—DEVELOPMENT ERRORS, E_d, FOR AREA A (110°W–50°W), JUNE–NOVEMBER 1970

			Number sampled	$\overline{E_d}$	$E_d \geqslant +5$	$\|E_d\| < 5$	$E_d \leqslant -5$	$\|E_d\| \geqslant 11$ dam
				dam		per cent		
Troughs	MET	AM	106	+6·0	58	37	5	17
		RE	57	−0·1	23	61	16	
	NMC	AM	106	+1·6	31	56	13	12
		RE	57	−0·4	24	52	24	
Ridges	MET	AM	55	+0·9	17	76	7	9
		RE	95	+4·3	41	57	2	
	NMC	AM	55	−1·7	12	63	25	3
		RE	95	−1·1	14	67	19	

An explanation of the symbols is given in the glossary.

TABLE VI—DEVELOPMENT ERRORS, E_d, FOR AREA B (50°W–00°), JUNE–NOVEMBER 1970

			Number sampled	$\overline{E_d}$	$E_d \geqslant +5$	$\|E_d\| < 5$	$E_d \leqslant -5$	$\|E_d\| \geqslant 11$ dam
				dam		per cent		
Troughs	MET	AM	86	+3·5	35	60	5	15
		RE	96	−4·5	8	46	46	
	NMC	AM	86	+2·1	29	55	16	12
		RE	96	−2·8	11	49	40	
Ridges	MET	AM	78	−4·4	2	47	51	
		RE	89	−1·4	12	65	23	8
	NMC	AM	78	−5·2	nil	36	64	7
		RE	89	−2·7	5	57	38	

An explanation of the symbols is given in the glossary.

$E_m \leqslant -5°L$) were 30 for MET and 31 for NMC; the corresponding figures for ridges were 34 (MET) and 26 (NMC).

(b) *Development errors* (Table VI). As in area A, mean development-errors are directly biased by the mean stationary-mode error, $(\overline{E_{ij}})_s$, which is negative over much of the North Atlantic in both MET and NMC.

A comparison of the Δ values in Table X indicates again that NMC was the more efficient in the handling of trough development although this superiority was not as great as it was in area A. For ridge development this is the only area in which the Δ figures of MET compare favourably with those of NMC.

The fact that Δ values for this area over the North Atlantic exceed the corresponding values in both areas A and C (except in the case of MET ridges) is probably largely due to the greater development-rates usually associated with this area, particularly the western half, and the relative sparsity of observations contributing to greater uncertainty in the initial objective analyses. This latter characteristic of area B probably also explains the high degree of similarity in performance between the two models in that it is generally accepted that the performance of the simpler vorticity-type models usually compares very favourably (up to 48 hours) with that of the more sophisticated multi-level PE models in areas where initial data are sparse, particularly at the 500-mb level.

Results for area C (00°–40°E).

(a) *Movement errors* (Table III and Figure 2(c)). As in area B, there was little to choose between MET and NMC in the handling of trough movement in area C, the mean movement-errors for both ranging from about 0°L for the slowest-moving troughs to about 6°L for the fastest. The figures for ridge movement, however, showed a marked difference in handling between MET and NMC. Most of the discrepancy can be explained in terms of the local west-to-east gradients of $(\overline{E_{ij}})_s$ (i.e. $\partial(\overline{E_{ij}})_s/\partial x$). In NMC (for the period June–November) the mean stationary-mode error changes rapidly from negative to positive from about 10°W to 40°E($\partial(\overline{E_{ij}})_s/\partial x > 0$). In MET, by direct contrast, the gradient is negative. The overall effect of these contrasting gradients is a systematic westward displacement of MET forecast ridge axes with respect to their NMC counterparts; for forecast troughs the relative displacement is eastward. As mentioned earlier the magnitudes of such displacements would be small ($< 1°L$) in the majority of cases, but for broad troughs and ridges, and particularly for blocking ridges, it may exceed 3° or 4°L and would probably be of sufficient magnitude in the mean to account for a large part of the discrepancy between MET and NMC mean ridge-movement errors. For troughs the effect is reversed and MET forecast troughs would be expected to be less slow than their NMC counterparts. The fact that this is not evident may indicate an *intrinsic* superiority of NMC for both trough and ridge movement. In the hypothetical absence of the existing contrasts in $(\overline{E_{ij}})_s$ gradients in the two models, the performance of NMC would probably be consistently superior to that of MET for both trough and ridge movement.

TABLE VII—DEVELOPMENT ERRORS, E_d, FOR AREA C (00°–40°E), JUNE–NOVEMBER 1970

			Number sampled	$\overline{E_d}$	Percentage of troughs/ridges with: $E_d \geqslant +5$	$\lvert E_d \rvert < 5$	$E_d \leqslant -5$	$\lvert E_d \rvert \geqslant 11$ dam
				dam	per cent			
Troughs	MET	AM	79	−0·7	20	57	23	17
		RE	70	−5·0	2	48	50	
	NMC	AM	79	+1·4	35	43	22	9
		RE	70	−0·4	16	60	24	
Ridges	MET	AM	55	−5·6	nil	41	59	5
		RE	87	−2·0	7	67	26	
	NMC	AM	55	−0·3	15	68	17	6
		RE	87	+0·9	25	62	13	

An explanation of the symbols is given in the glossary.

TABLE VIII—MOVEMENT ERRORS, E_m, FOR THE THREE AREAS COMBINED (110°W–40°E), JUNE–NOVEMBER 1970

	M	MET $\overline{E_m}$	MET σ_m	NMC $\overline{E_m}$	NMC σ_m	Number sampled
		degrees of longitude				
Troughs	⩽9	−0·2	3·6	+0·2	3·9	134
	10–19	−2·0	3·8	−1·5	4·0	142
	20–29	−3·8	3·9	−3·3	3·5	116
	30–39	−5·9	5·2	−5·1	5·5	64
	⩾40	−6·3	6·7	−7·5	7·3	36
Ridges	⩽9	−0·4	3·9	+1·0	3·8	156
	10–19	−2·8	4·3	−0·6	4·0	137
	20–29	−4·1	4·0	−2·7	4·0	104
	30–39	−5·9	5·3	−4·5	4·7	46
	⩾40	−9·2	5·6	−6·1	5·2	16

TABLE IX—DEVELOPMENT ERRORS, E_d, FOR THE THREE AREAS COMBINED (110°W–40°E), JUNE–NOVEMBER 1970

			Number sampled	$\overline{E_d}$	Percentage of troughs/ridges with: $E_d \geqslant +5$	$\lvert E_d \rvert < 5$	$E_d \leqslant -5$	$\lvert E_d \rvert \geqslant 11$ dam
				dam	per cent			
Troughs	MET	AM	271	+3·1	39	51	10	16
		RE	223	−3·8	10	50	40	
	NMC	AM	271	+1·7	32	52	16	11
		RE	223	−1·4	16	53	31	
Ridges	MET	AM	271	−3·1	6	54	40	7
		RE	188	+0·4	21	62	17	
	NMC	AM	271	−1·9	9	54	37	5
		RE	188	−1·1	15	62	23	

TABLE X—DEVELOPMENTAL EFFICIENCY, Δ, FOR THE THREE AREAS

		Area A 110°W–50°W	B 50°W–00°	C 00°–40°E	All three areas
			decametres		
Troughs	MET	+6·1	+8·0	+4·3	+6·9
	NMC	+2·0	+4·9	+1·8	+3·1
Ridges	MET	−3·4	−3·0	−3·6	−3·5
	NMC	−0·6	−2·5	−1·2	−0·8

[$\Delta = \overline{E_d}$ (AM) $- \overline{E_d}$ (RE)]

In real terms, however, the slowest-moving ridges were better handled by MET ($\overline{E_m} = -0{\cdot}5°L$ for $M_R \leqslant 9°L$), the corresponding NMC-forecast ridges being too fast ($\overline{E_m} = +\ 1{\cdot}9°L$). For all other ridges ($M_R \geqslant 10°L$) NMC performed much the better (by about 3°L in the mean). Percentages of forecast ridges with movement error greater than 4°L slow (Table IV) were 25 for MET and only 13 for NMC.

(b) *Development errors* (Table VII). The direct biasing by the mean stationary-mode error was again evident; for NMC $(\overline{E_{ij}})_s$ is small but positive in area C, and for MET it is negative and of appreciable magnitude. The direct biasing of this mode of error is illustrated in the mean development errors for this area where the most significant errors occurred in MET amplifying ridges where $\overline{E_d} \approx -6$ decametres compared with the NMC figure of $-0{\cdot}3$ decametres. The handling of ridge development by NMC was very good in this area particularly in cases where amplifying ridges evolved to form blocking highs. The local biasing conditions obviously favour NMC in amplifying-ridge cases since the negative non-stationary-mode error associated with amplifying ridges is usually balanced by positive $(\overline{E_{ij}})_s$ in NMC and accentuated by negative $(\overline{E_{ij}})_s$ in MET. In MET, 59 per cent of amplifying ridges were underforecast by more than 4 decametres compared with the corresponding NMC figure of only 17 per cent.

The Δ figures for area C (Table X) again illustrate the superior developmental efficiency of NMC for both troughs and ridges.

Conclusions. A slight overall intrinsic superiority of the 6-level PE model (NMC), both in movement and development, was evident in areas A (Rockies to Newfoundland) and C (western and central Europe).

In area A the intrinsic superiority of NMC was almost certainly considerably enhanced by superior Rockies modelling.

In area B there was little or no significant difference between the two models except in trough development (where NMC was better). The relative sparsity of initial data in this area makes the performance of the simpler 3-level vorticity model (MET) difficult to better.

In area C the modification of the apparent intrinsic superiority of NMC by the contrasting mean stationary-mode error fields and their west-to-east gradients was such that, in real terms, there was little to choose between the models for trough movement, while for ridge movement NMC was considerably less 'slow' than MET.

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GLIDER FLIGHT IN THE LOWER STRATOSPHERE ABOVE CUMULONIMBUS CLOUDS

By T. A. M. BRADBURY

Summary. On 9 May 1971 Mr Michael Field, flying an 18-m-span glider, climbed to nearly 8700 m in a cumulonimbus cloud between Swindon and Oxford. He then flew upwind of the cloud and climbed in wave lift to 12 960 m, about 4 km above the tropopause. Radar observations showed no sign of lee waves in the troposphere below 5 km and it appears that the high-level waves used by the glider were caused by the convective clouds extending up into a layer of strong winds near the tropopause.

Account of the flight. Mr Field, flying a Slingsby Skylark 4 glider, left Booker airfield, near High Wycombe, at 12 GMT on 9 May 1972 and was aero-towed upwind to an area clear of the airways radiating from London. At about 13 GMT he reached 11 520 ft (3511 m) in a large cumulus cloud and was then able to fly farther upwind to a large bank of cumulonimbus. He reached this cloud at Cricklade, about 5 miles (≈8 km) north-north-west of Swindon, and, after penetrating some distance into cloud, located the region of upcurrents. This part of the climb began at about 3100 ft (945 m) and continued up to 28 520 ft (8693 m).

When the rate of climb decreased to zero and the cloud became lighter Mr Field steered west-south-west to reach clear air. The outside of the glider was by then covered with ice. Inside the cockpit the condensation had frozen, covering the canopy and instruments with hoar-frost. The artificial horizon had been kept clear by constant scraping of the glass but other instruments were obscured at this time and as a result the pilot at first misread his height as about 18 000 ft when in fact it was 28 000 ft.

The canopy ice prevented the pilot from observing just when clear air had been reached. The glider has clear-vision panels but the ice was too thick for these to be opened. As a result the pilot could not give any description of the appearance of the clouds, nor could he note his position in relation to them. This lack of visual observation is a severe handicap in analysing the remainder of the flight.

When the glider had descended to 26 000 ft (8077 m) it reached an area of smoothly rising air which the pilot recognized as wave lift. He then began a series of wide 'S' turns keeping to an average heading of west-south-west. This is a pattern of flight commonly used in wave soaring when the forward speed of the glider is greater than the horizontal wind speed. Since the air-speed indicator was not functioning then, the pilot trimmed the glider to a speed which seemed comfortably above the stall. At 30 000 ft the true air-speed is estimated to have been between 80 and 90 kt (40–45 m/s), which was much more than the environmental wind at that level.

At 36 000 ft (nearly 11 000 m) the pilot lost the area of lift and began a search to regain it. During this search he descended to 34 500 ft (about 10 500 m). At this level he experienced about a minute of severe 'cobblestone' turbulence. The true airspeed at this level was probably between 90 and 100 kt (45–50 m/s). When the turbulence ceased the glider entered strong lift. The rate of climb seemed rapid at first, but soon decreased to a slower rate than before. When the rate of climb became negligible the pilot abandoned the ascent at a height which was later confirmed as 42 520 ft (12 960 m) above sea level.

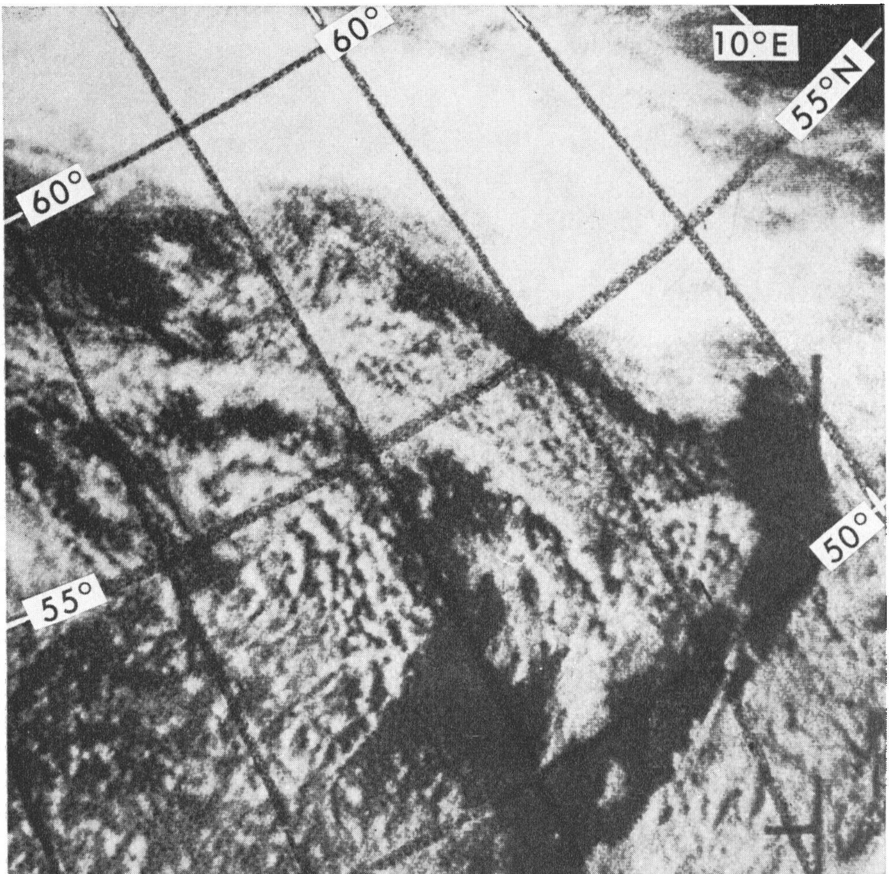

PLATE I—SATELLITE PHOTOGRAPH OF CLOUD PATTERN OVER THE BRITISH ISLES AT 12 GMT, 9 MAY 1972

See page 113.

Photograph by D. Tribble

PLATE II—EXAMPLE OF EXTENSIVE VARIED CIRRUS IN THE AUSTRIAN TIROL

Looking north-west at approximately 1700 GMT. See page 120.

Photograph by D. Tribble

PLATE III—EXAMPLE OF EXTENSIVE VARIED CIRRUS IN THE AUSTRIAN TIROL

Looking west at approximately 1730 GMT. See page 120.

Photograph by D. Tribble

PLATE IV—EXAMPLE OF EXTENSIVE VARIED CIRRUS IN THE AUSTRIAN TIROL

Looking north-west at approximately 1730 GMT. See page 120.

During the descent, but while still above the freezing level, the tailplanes were twice struck by pieces of ice which, it is assumed, had broken away from the wings. The air-brakes were in use to increase the rate of descent and it may be that the buffeting and vibration they caused shook off some of the ice. The freezing level was about 4000 ft (1220 m) and consequently the ice did not clear completely before landing. Since the forward view was still too poor for the pilot to return to the airfield he made a landing in a field at the foot of the Chilterns several miles north-west of Booker.

Vertical currents encountered during the climb. The rates of climb achieved by the glider have been calculated from a copy of the barograph trace provided by Mr Field. The original trace shows only the pressure curve; heights and times have been superimposed after calibration (Figure 1).

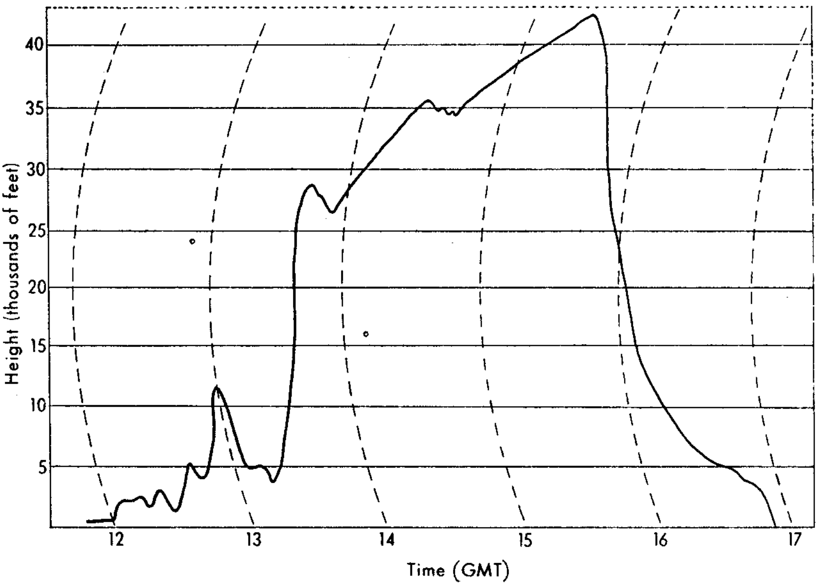

FIGURE 1—ENLARGED COPY OF BAROGRAPH TRACE SUPPLIED BY MR FIELD

Calibration lines for time and height have been added.

The vertical velocity of the air currents has been derived by adding the calculated sinking speed of the glider to the mean rate of climb. The sinking speed of a Skylark 4 at various airspeeds has been measured by several independent test groups in recent years and the curves show a satisfactory measure of agreement. Figure 2 shows the calculated sinking speed of a Skylark 4 flying straight, at an indicated airspeed of 55 kt, at altitudes from sea level up to about 55 000 ft. The full curve is for a glider in clean condition, the pecked curve is the result of adding 50 per cent to the sinking speed to allow for the effect of ice. Unfortunately there are no figures published for gliders in this condition. Various glider pilots were consulted and this estimate was thought to be reasonable. In view of the uncertainty no additional

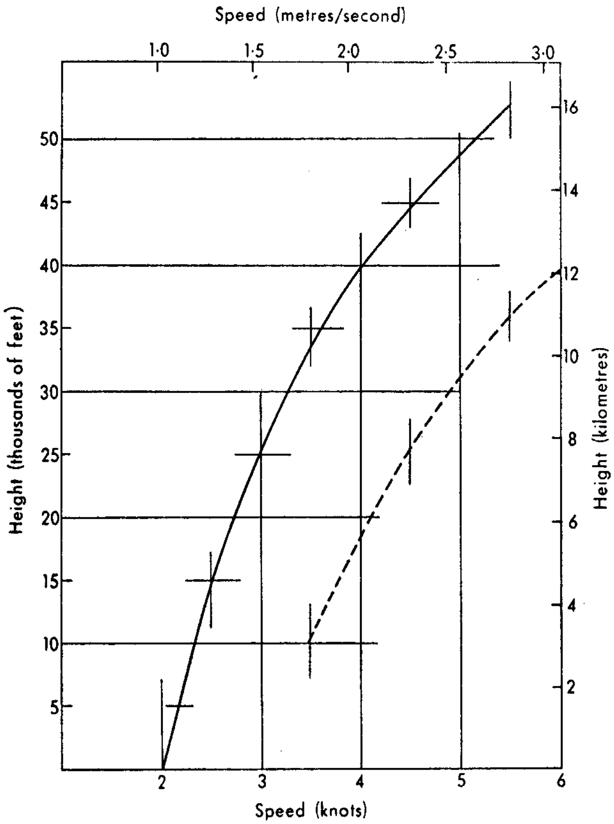

FIGURE 2—CALCULATED SINKING SPEED OF SKYLARK 4 GLIDER FLYING AT AN INDICATED AIRSPEED OF 55 KNOTS AT VARIOUS ALTITUDES

——— Glider in clean condition. — — — Estimated performance when ice had formed.

correction was made for the change of Reynolds number. It has been estimated that this would only amount to about 5 per cent decrease in glider performance at levels near the tropopause.

The average rate of climb for the ascent inside the cumulonimbus works out at about 9·5 kt, indicating vertical currents of at least 13 kt (6·5 m/s). However, the rate of climb was less than this at the beginning and end of the climb in cloud. Between the heights of 10 000 and 25 000 ft (3000 to 7600 m) the rate of climb was about 15 kt (7·5 m/s) suggesting upcurrents of at least 19 kt (9·5 m/s). These rates of climb are not remarkable for the size of cloud and suggest that the glider was not in the strongest lift.

In clear air the vertical currents were much weaker. From 26 000 to 36 000 ft (7925 to 10 970 m) the rate of climb averaged 3 kt (1·5 m/s). This probably represents a vertical current of about 8 kt (4 m/s).

The final part of the climb from 34 000 ft (10 360 m) to the top showed an average rate of ascent of 1·8 kt (0·9 m/s) but allowing for the greater rate of sink the vertical velocity of the air was probably again about 8 kt (4 m/s).

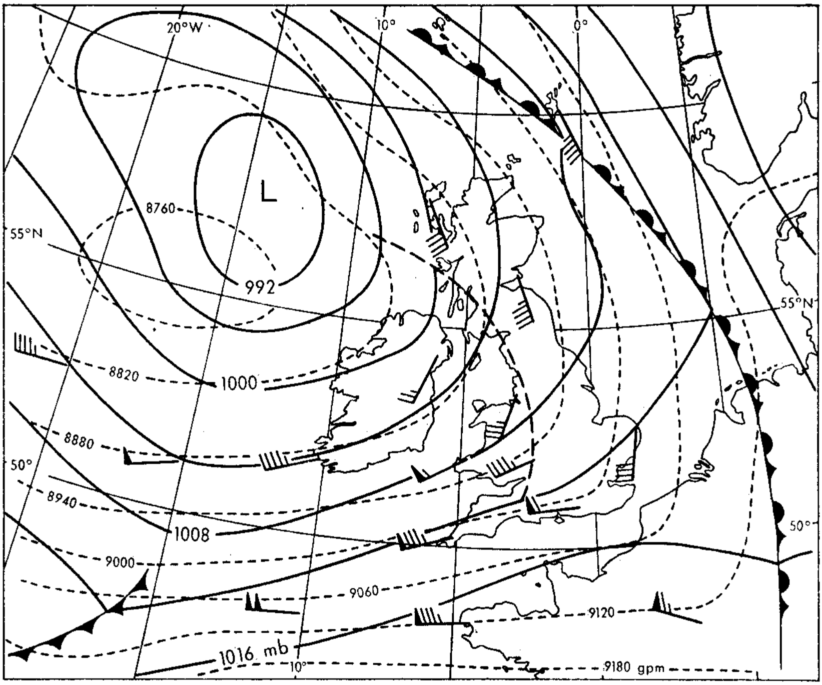

FIGURE 3—SURFACE CHART FOR 12 GMT, 9 MAY 1972, WITH 300-MILLIBAR CONTOURS AND WINDS ADDED

——— Surface isobars. - - - - 300-mb contours. — — — Line of shower cloud.

Meteorological conditions in the area of the flight. The midday chart (Figure 3) shows a depression west of the Hebrides with an unstable south-westerly airflow over England. Minor troughs were moving north-east across the country and one of these troughs produced a continuous line of shower cloud which may be seen in the satellite photograph (Plate I). Arrows showing the winds reported at 300 mb have been added to the surface chart to indicate the presence of a jet-stream which was extending towards Brittany. Figure 4 shows cross-sections of the upper winds along a line from Long Kesh in Northern Ireland to Camborne in Cornwall, and also from Long Kesh to Crawley in Sussex. These cross-sections are approximately at right angles to the wind, and show the edge of the jet-stream. The mean winds for the climb were estimated from these cross-sections.

Movement of shower clouds. The radar at the Meteorological Research Unit, Malvern, recorded the pattern and movement of numerous showers which occurred over the Midlands and southern England that afternoon. The long band of cloud shown on the satellite photograph appeared on the radar as a number of separate showers. The cloud mass visible over Devon and the Bristol Channel on the photograph was later tracked by radar. Its movement is shown in Figure 5. From the times given by Mr Field it appears that this was the cloud mass in which the glider began its big climb.

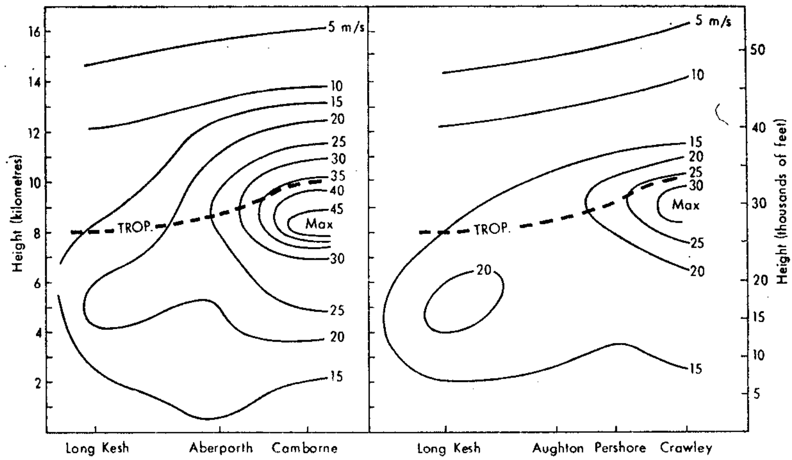

FIGURE 4—CROSS-SECTIONS OF WIND SPEEDS AT 12 GMT, 9 MAY 1972: LONG KESH TO CAMBORNE AND LONG KESH TO CRAWLEY

Aberporth winds are from the 11-GMT sounding and Pershore winds are from the 10-GMT sounding.

The pattern of cloud cells could be tracked for up to two hours and showed that the average speed was 24 kt ($\pm$ 2 kt) from a direction of 240°.

Vertical extent of cumulonimbus clouds. Although cloud tops had been measured by radar that morning there were no height readings for the afternoon and it was necessary to estimate the vertical extent. The height to which convective clouds can rise is partly dependent on their distribution;[1] large masses of cumulus are often found to extend higher than isolated clouds. The cloud mass in which the glider climbed formed part of a very active system several miles wide and about 70 miles ($\approx$113 km) long. The radar echoes photographed at Malvern were so strong that a number of cells could still be seen when the attenuation had been increased to 40 db. It seems likely that tops reached the tropopause which was between 28 000 and 30 000 ft ($\approx$8500–9100 m). Figure 6 shows the Aberporth 11-GMT radiosonde ascent which was the most representative sounding.

Vertical wind shear and 'thermal waves'. Figure 7 shows the vertical wind shear plotted in relation to the speed of the clouds together with the assumed airflow over the cumulonimbus in which the glider climbed.

It has been observed that cumulus containing powerful convective up-currents are able to rise through a layer of stronger winds aloft without experiencing the tilting or distortion of the clouds which occurs with weaker convection. When such a vigorous cumulus cloud extends into a faster-moving airstream aloft the upcurrents act as an obstruction to the horizontal flow aloft. Some of the surrounding air is probably entrained into the expanding cloud but the rest of the flow is deflected round or over the cloud.

Kuettner[2] suggests that for a vertical wind shear of 3 kt per 1000 ft (5 m/s per km) a glider may be able to ascend in clear air close to the upwind side of a cumulus at about 2 kt (1 m/s). The technique is very similar to that used for hill soaring.

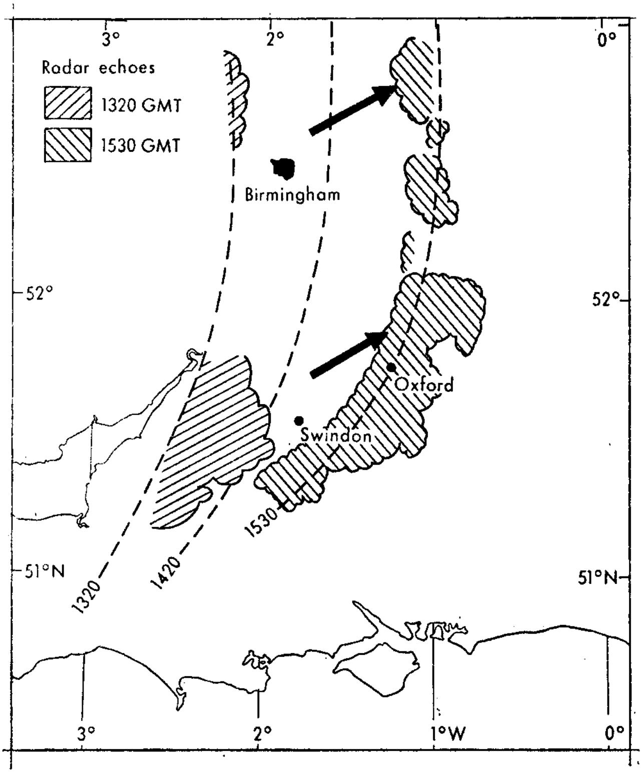

FIGURE 5—MOVEMENT OF CUMULONIMBUS BELT DURING THE PERIOD OF THE GLIDER'S CLIMB, AS SHOWN BY MALVERN RADAR

Hatching shows the eastern edge of the cloud echo at 1320 and the entire area of echo at 1530 GMT. Arrows show movement of echoes.

When the air between and over the cumulus clouds is relatively stable most of the flow is likely to be deflected round rather than over the clouds. This seems to be confirmed by the observations of glider pilots that it is rarely possible to climb much above the top of scattered cumulus. However, long lines or 'streets' of cumulus clouds appear to influence the airflow to greater heights. Jaeckisch[3] gives examples where cumulus formed long streets beneath an inversion with stable air above. The wind at cloud level was parallel to the cumulus streets but above the inversion the wind had a component at right angles to the streets. A wave-like flow was observed in the stable air aloft and gliders were able to climb several thousand feet above the cloud tops.

This wave-like flow over cumulus clouds has been termed 'thermal waves' or 'cumulus waves' to distinguish it from the orographically caused lee waves.

Thermal waves or lee waves? The conditions under which thermal waves can form are similar to those for the development of lee waves and it may be difficult to separate the two processes. There are many observations of the effect of lee waves on the distribution of convective clouds. These show

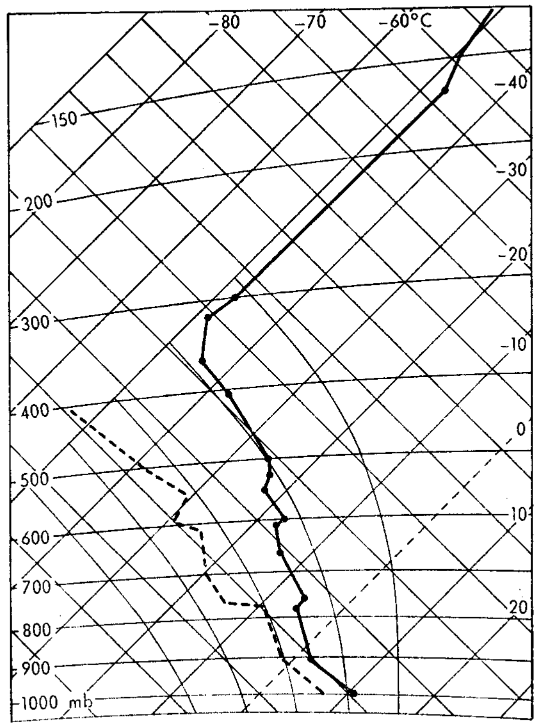

FIGURE 6—TEPHIGRAM OF THE ABERPORTH RADIOSONDE ASCENT AT 11 GMT, 9 MAY 1972

•——• Dry bulb. ---- Dew-point.

that cumulus clouds are suppressed in wave troughs and enhanced under wave crests. There are at present relatively few observations of waves produced exclusively by the underlying thermal activity. However, Townsend[4] has shown that convective currents can produce wave motion in the stable layer above.

The great depth of instability on 9 May 1972 makes the development of lee waves seem unlikely. The possibility cannot be excluded for that reason alone because there are now a number of observations of large cumulus and even of cumulonimbus extending up through levels at which gliders were soaring in lee waves. These observations show that lee waves can occur in close proximity to large convective clouds. The likelihood of lee waves on this occasion can be ruled out by the report from Malvern.

The high-powered radar at Malvern is able to detect waves in the troposphere.[5] A few hours before the glider began its climb the Malvern radar had been scanning the sector upwind towards Wales. The range/height pictures showed more than one quasi-horizontal layer in the mid troposphere and if wave flow had occurred it should have been visible as an undulation in one of these layers. The radar records show the development of convective clouds, with one top reaching the 5-km level, but no sign of wave flow.

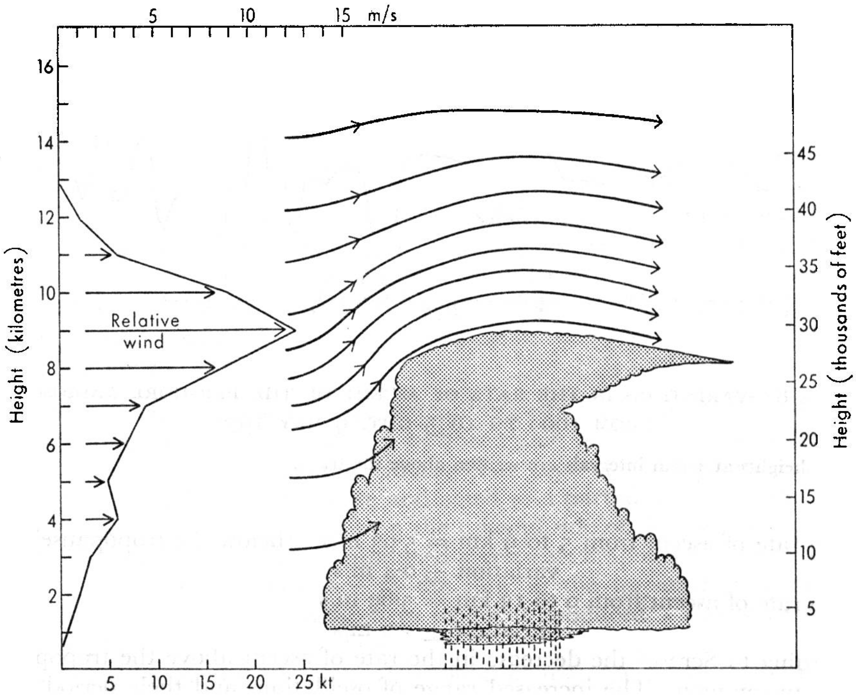

FIGURE 7—VERTICAL WIND SHEAR IN RELATION TO THE CUMULONIMBUS WITH ASSUMED PATTERN OF AIRFLOW OVER IT

Other gravity waves. Where jet streams exist the conditions of stability and vertical wind shear often favour the development of gravity waves. Kuettner[6] considered the possibility of such waves being used by a glider. Satellite photographs have revealed a number of examples of transverse waves on the long bands of jet-stream cirrus. Roach[7] has given examples of waves at high level far out over the Atlantic in regions where there was a strong upper flow ahead of a developing depression.

The situation on 9 May 1972 showed some similarity to the examples quoted by Roach. The Pershore 10-GMT radiosonde ascent was therefore examined to see if the balloon showed any periodic variations in the rate of ascent which might indicate wave motion.

Existence of high-level waves indicated by the balloon sounding. A radiosonde was launched from Pershore about two hours before the glider took off. The height of the balloon was measured at 20-s intervals and from these values the rate of ascent was plotted. Figure 8 shows the observed variations from about 5 km upward. Values below 5 km are not included here because it was considered that convective currents influenced the upward velocity.

In the diagram time is plotted on the *x*-axis and the rate of ascent is plotted on the *y*-axis. The actual heights at 4-min intervals are written above the curve. The results are summarized overleaf.

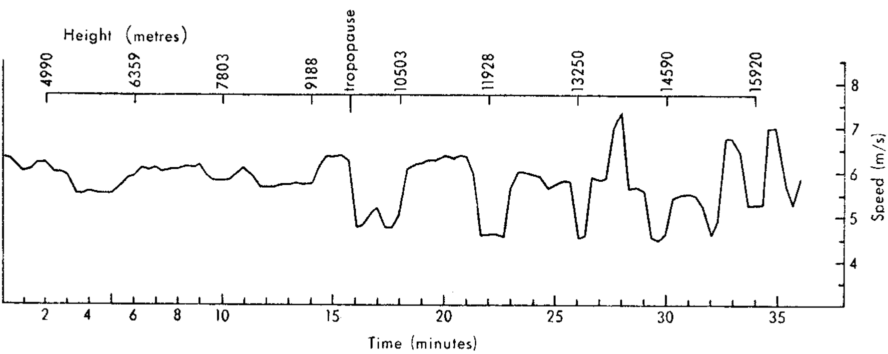

FIGURE 8—VARIATIONS IN THE RATE OF ASCENT OF THE PERSHORE RADIOSONDE FROM 1000 TO 1035 GMT, 9 MAY 1972

Actual heights at 4-min intervals are written above the trace.

Mean rate of ascent from 5 to 9 km = 5·93 m/s (below the tropopause)
variation ± 0·4 m/s
Mean rate of ascent from 9 to 13 km = 5·69 m/s
variation ± 1·0 m/s

According to Scrase[8] the decrease in the rate of ascent above the tropopause is not uncommon. The increased range of oscillations and their period may however be significant. The period of the first oscillation is about 320 s; subsequent periods grow shorter with increasing altitude.

These oscillations may represent weak waves in the lower stratosphere, but if so the associated vertical currents are very much weaker than those found by the glider a few hours later.

Stratospheric wave and the underlying cumulonimbus. While the glider was ascending in the lower stratosphere its average cross-country speed was not much less than the speed of the cumulonimbus beneath. It is probable that the two stages of the ascent above the tropopause used two different waves which moved in phase with the clouds beneath.

If it is assumed that the period of 320 s was close to the natural period of oscillation of the air just above the tropopause and the wave kept in phase with the cloud below moving at 24 kt (12 m/s) then the wavelength would be nearly 4 km.

Clear-air turbulence (CAT). It is not unusual to experience CAT close to areas of wave flow particularly if there is strong wind shear in the vertical. Radar studies[revealed that CAT developed when large-amplitude Kelvin–Helmholtz billows with wavelengths up to 4 km broke down.

The glider experienced about one minute of severe 'cobblestone' turbulence at about 34 500 ft (≈10 500 m) after which the air was found to be rising rapidly. It seems possible that the glider flew through a breaking wave at this stage. The Richardson numbers, calculated for layers of depth 200 m and 400 m from the Pershore sounding a few hours earlier, showed no sign of the very low values of Ri normally associated with this class of turbulence. There were however no strong vertical currents when the balloon ascended into the lower stratosphere. The development of the strong upcurrents may have produced local concentrations of wind shear which did not exist at the time of the sounding.

A special investigation into CAT was being undertaken on this day and a large number of aircraft reports were available. There was only one report, from a large military jet aircraft, which coincided fairly closely in time and height with the glider observation. The jet flew from west to east at 35 000 ft just north of the area of the climb. No turbulence was observed there although light turbulence had been encountered during the climb through the tropopause farther west. This negative report, together with the fact that the glider only once encountered turbulence, suggests that the CAT was a very local phenomenon, probably associated with the altered airflow above the cumulonimbus.

Conclusions. A jet stream was extending eastwards over Brittany, and the strengthening upper winds on the northern side of this jet passed over an irregular line of cumulonimbus clouds. The tops of these clouds extended up to the base of the stratosphere and acted as a partial barrier to the strong upper winds. As a result the air on the upwind side of the clouds was forced to rise over the cloud tops and produced a vertical component of air of at least 8 kt (4 m/s). The disturbance to the flow in the upper troposphere also extended into the lower stratosphere where it produced a wave-like motion at least 4 km above the tropopause.

By flying out of the cumulonimbus cloud at high level and on the upwind side the glider entered a region of ascending air and was able to climb through the tropopause and well into the lower stratosphere.

This is the first report of such a phenomenon at high level but there have been a number of observations of similar phenomena on a smaller scale when cumulus developed in a vertical wind shear.

The turbulence encountered in clear air above the cumulonimbus cloud suggests a localized breakdown of the wave flow. This type of CAT may be a regular occurrence when wave flow develops over cumulonimbus clouds but if so it probably only affects small areas.

Acknowledgements. The thanks of the author are tendered to the staff of the Meteorological Research Unit at Malvern who provided a very large number of tracings from radar plan-position-indicator photographs, computed a radiosonde ascent of exceptional detail, and supplied a series of radar range/height-indicator photographs showing airflow over and to lee of the Welsh mountains.

The author is also grateful to Mr S. G. Cornford, Meteorological Office, Bracknell, who provided data from reports of CAT and to Dr J. P. Kuettner, World Meteorological Organization, for information on 'thermal waves'.

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AN EXAMPLE OF EXTENSIVE VARIED CIRRUS IN THE AUSTRIAN TIROL

By E. N. LAWRENCE

Plates II, III and IV show an unusual display of cirrus cloud. The pictures were taken on 6 August 1954, south of Kitzbühel (approximately 47½°N, 12½°E) in the Austrian Tirol.

At the time, there was a pre-sunset sky of crimson red, particularly at the lower or lighter part of the sky, illuminated by the sun behind the silhouetted ridge in the photographs.

Surface charts show that the cirrus did extend well to the north-east and south-west of the Tirol however and its more general development was probably caused by ascending motion in the upper troposphere associated with the approaching trough at 300 mb (see Figure 1). The eastern edge of this band of cirrus is estimated to have cut latitude 50°N at longitude 5°–10°E at 18 GMT on 5 August and at 10°–15°E 24 hours later, when the eastern part of the band passed through or rather to the north-west of Kitzbühel.

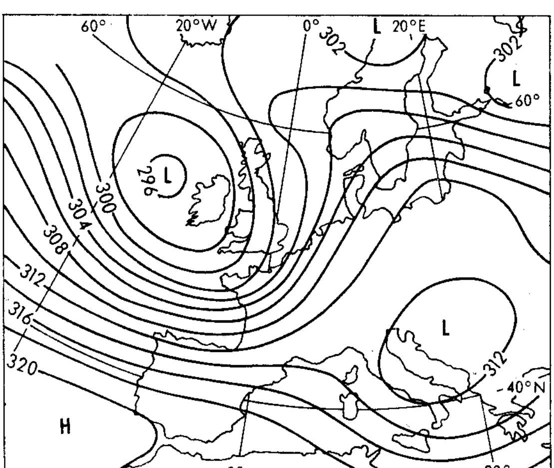

FIGURE 1—CONTOUR CHART OF THE 300 MILLIBAR SURFACE AT ABOUT 15 GMT, 6 AUGUST 1954

Contours at 200-ft intervals

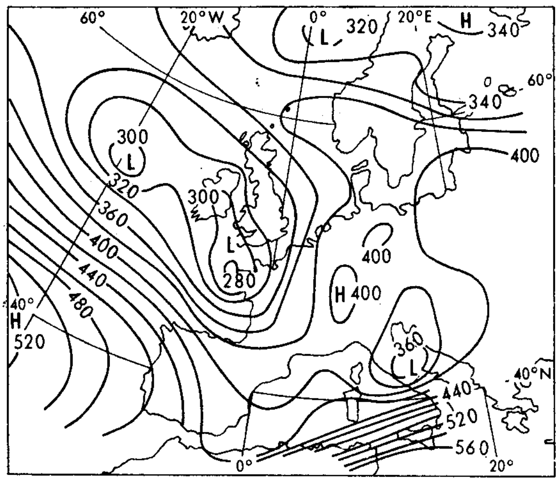

FIGURE 2—CONTOUR CHART OF TROPOPAUSE HEIGHT AT ABOUT 15 GMT, 6 AUGUST 1954

Contours at 2000-ft intervals, values are in hundreds of feet.

Weak pressure gradients rather eliminate the possibility of orographic cirrus but the 'isolated' shower in the region on the previous day suggests the possibility of some residual cirrus.

A striking feature of the upper-air patterns was the strong south-westerly gradient (about 1 in 50 over 150 miles ($\approx$240 km)) of the contour lines of the height of the tropopause over northern Italy and the northern Adriatic Sea at 15 GMT on the 5th. By 15 GMT on the 6th this gradient had moved south to Tunisia, Sicily and southern Italy, leaving a high cell centred at 48°N, 8°E (see Figure 2).

REVIEWS

Profiles of wind, temperature, and humidity over the Arabian Sea, by F. I. Badgley, C. A. Paulson and M. Miyake. 282 mm × 222 mm, pp. 62, *illus.*, University of Hawaii Press, 535 Ward Avenue, Honolulu, Hawaii 96814, 1972. Price: $7.50.

This volume has two parts, the first describing and presenting the observations and the second analysing them. The measurements were made in late February and early March 1964 at locations around 19°N 72°E, 20°N 69½°E, and 20½°N 71½°E, in the Arabian Sea. The equipment used consists of a stabilized floating carrier known as 'Mentor' which supports an 8·5-m mast and which, in use, is kept well upwind of the tending ship by means of a sea-anchor. The instrumented boom projects into wind and is mounted on a carriage which runs up and down the mast, stopping at six selected levels for sampling times of about 15 seconds each. A complete sequence of measurements takes about 2 minutes and was repeated as often as possible during each test run of about 40 minutes, the outputs (wind speed, air temperature and wet-bulb depression) being recorded on magnetic tape. Checked data from 118 test runs, consisting of mean values for six levels between 114 and 815 cm of wind speed, temperature and specific humidity, are presented. Also included are wind direction and sea surface temperature during each run and SHIP and PILOT SHIP observations made from the escorting ship at main synoptic hours on the days on which profiles were measured.

In Part 2 an analysis is carried out of 110 sets of data, the other 8 being excluded because fetches were less than 50 km. Possible errors in the measurements are first considered in some detail. It is shown that errors due to buoy motion, to study which special measurements were made of pitch, roll and vertical acceleration, could be safely ignored. Interference due to the buoy pontoons is believed to have caused anomalous (low) wind speeds at the lowest sampling level but it is concluded that the resulting errors in computing friction velocities from the profiles could be neglected. The main uncertainty arose from sampling error, each level being sampled for only about one-eighth of the time, and this is discussed at some length. It was minimized by comparing the readings of the travelling probe with those from a fixed probe at the 4-m level and by adjusting the raw data accordingly. The standard deviations of the differences between the readings at the 4-m level indicated sampling errors of about 1·3 per cent in wind speed, 0·012 degC in temperature and 0·04 degC in wet-bulb temperature. Wave-generation theories predict that profiles over water should be different from those over solid surfaces, at least in the lower layers. To test this, 21 selected wind and humidity profiles, restricted to the higher speeds and near-neutral conditions, were combined but there were no major peculiarities in the mean profiles which could be attributed to wave-generation processes. Such effects could of course have been present below the lowest sampling level or might become more apparent at higher wind speeds than those encountered, all of which were below 9 m/s. Computed fluxes of momentum, heat and water vapour are tabulated for each run. The observations are shown to be well represented by the Businger–Dyer model for unstable conditions and by the log-linear equation for stable conditions; the profiles are thus indistinguishable from those measured over land. A drag coefficient of about 0·0014 for wind speeds in the range 2–8 m/s, but increasing slowly with increasing wind speed, is indicated. Finally, comparisons of the computed water-vapour fluxes, on some occasions with areal evaporation estimates based on simultaneous observations from aircraft, show reasonably good agreement. As the authors themselves remark, observations at higher wind speeds would be very desirable in future measurements of this type.

The work is the sixth in the series of International Indian Ocean Expedition meteorological monographs and maintains their high standard of presentation. A few minor errors were noted, however, the most important being that Figure 9 is printed over the caption for Figure 8 and vice versa.

H. C. SHELLARD

Geography from space, by E. C. Barrett. 290 mm × 210 mm, pp. 98, *illus.*, Pergamon Press Ltd, Headington Hill Hall, Oxford OX3 0BW, 1972. Price: 95p.

The outstanding feature of this book is the extremely high quality of the many coloured photographs, mostly taken from satellites. They may be awe-inspiring, as the view of the Earth from the Moon (Plate 1.1) and of the Kashmir Himalayas from GEMINI V (Plate 17.11); or strikingly informative, as the GEMINI IV view of the Nile delta (Plate 7.1); or of tranquil beauty, as the conventional photograph of convective cloud off the coast of southern Queensland, Australia (Plate 11.2).

The title of the book is rather misleading, the subtitle 'modern readings in physical geography' being a better description of the contents. Approximately half of the book is concerned with weather and climate (including hurricanes and the south Asian monsoon) and there are also chapters devoted to ocean currents, the Nile delta, structure of coasts, the polar regions, regions of high relief, patterns of erosion, and the use of land. Every chapter is illustrated by one or more excellent satellite photographs including examples of varicoloured maps (made with an infra-red radiometer) of the sea surface temperature in the vicinity of the Gulf Stream (Plate 11.1), and of different types of land surface such as forest, farmlands and rivers (Plates 19.1, 19.2, 19.3).

The text is clearly written and is interspersed with stimulating questions for the benefit of geography students, but even though the treatment of the meteorological sections is elementary, the author could have improved on the definition of isobars on weather maps (page 18) and of advection (page 72). Also in explaining the formation of rain (page 8) he mentions only the coalescence mechanism.

The book is recommended as an introduction to the study of weather and climate from a modern 'space-age' standpoint.

F. E. LUMB

NOTES AND NEWS

History of Eskdalemuir Observatory

The Superintendent, Eskdalemuir, who is bringing up to date a history of the Observatory, has asked if there are any pre-war Eskdalemuir staff still in the Office who might have interesting photographs (including pictures of themselves) taken at that time.

There may also be a number of retired members who served at the Observatory and who still receive the *Meteorological Magazine*. The Superintendent would like to obtain copies of any pictures not already available to him and, of course, he would arrange the copying.

Readers having suitable photographs are invited to get in touch with Mr P. R. Robinson, Superintendent, The Observatory, Eskdalemuir, Langholm, Dumfriesshire PG13 0QW.

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