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SOME EXAMPLES OF THE RAINFALL FORECASTS PRODUCED BY THE FINE-MESH VERSION OF THE 10-LEVEL MODEL

By P. G. WICKHAM

Summary. The rainfall forecasts over the British Isles, computed by the fine-mesh version of the 10-level model on four occasions during the summer of 1973, are displayed.

Current deficiencies in the formulation of certain physical processes in the model, notably the representation of convective rainfall processes and of topography, give rise to some substantial, but identifiable, errors in the rainfall accumulations forecast at individual grid points. However, from a synoptic viewpoint the computed forecasts often provide useful guidance on the character of the rainfall occurring in these situations.

The fine-mesh version of the 10-level model. A detailed description of this model was published in 1971.[1] Since that date a number of changes in the formulation of the fine-mesh model have been introduced, notably the adoption of a semi-implicit integration scheme. However, the modelling of the precipitation processes remains unchanged. At each time-step in the integration of the forecasting equations, equivalent to 12 minutes of real-time, forecasts of the rate of rainfall at the bottom level of the model (1000 mb) are made at each point of a horizontal grid which has a mesh size of 100 km. The accumulated rainfall total since the start of the forecast run is also recorded.

The forecast rainfall is produced in the model in two ways. Advection of water vapour by the three-dimensional motion of the model atmosphere may lead to the air at some level above a grid point becoming supersaturated. The superfluous moisture then condenses, falls and, subject to possible evaporation into drier layers below its original level, reaches the surface as rain. Rainfall produced in this way is referred to as ' dynamic rain'.

A superfluity of moisture in a layer above a grid point may also be produced as a result of the 'convective adjustment' process. This is a process, carried out after each time-step, in which the thicknesses of each successive pair of layers above a grid point are mutually adjusted so as to ensure that no unreasonable static instability develops at individual grid points. Since, in the current formulation of the model, the relative humidities of the adjusted layers are kept unchanged, any moisture in excess of that required to conserve the relative humidities is condensed and may eventually reach the surface. This is referred to as 'convective rain'.

It has been found in practice that, while the 'convective rainfall' forecast by the model normally occurs in areas where it is synoptically reasonable to expect showers, the quantity of convective rain forecast is usually very much less than the quantity of forecast dynamic rain and also very much less than the actual rainfall which occurs through showers or other convective systems. The 'total rate' of rain at any grid point is the sum of the dynamic and convective rates. In this article it is the total rate of rain and the total rainfall accumulations that are displayed.

General synoptic character of the early summer of 1973. For many months prior to June 1973 the weather in the British Isles was remarkably dry. During the first 10 days of June this dry weather continued and led to public warnings becoming increasingly frequent during this time, about the necessity of conserving water supplies.

Subsequently, during the following three weeks, there were four important frontal situations which affected the country. In terms of the actual rainfall accumulations, two of these situations were significantly wet in the southern half of England but dry elsewhere, while the other two were dry over England but brought rain to Scotland. Having regard to the national water shortage at this time, it was of some importance to be able to forecast correctly which of the fronts would produce a lot of rain and which would not.

An assessment of the synoptic value of the charts of forecast rates of rainfall. In this section some brief comments are made on each of the forecast charts in Figures 1–4, to illustrate their value to forecasters engaged on general synoptic duties. Each chart has also been given an assessment letter which, being subjective, is not likely to command universal agreement. However, the point of these assessment letters is to provide an indication of the value of the forecasts as a whole rather than individually. This is done in Table I. The definitions of the letters are to be found on page 212.

Figures 1–4 illustrate each of the four frontal situations in turn. Each covers a 48-hour period and shows actual charts at 12-hour intervals. The isobars are drawn at 4-mb intervals and the frontal positions have been taken from the *Daily Weather Report*. The extent of the frontal rain has been sketched in from the reported synoptic observations, thus distinguishing areas of mainly slight rain (hatched), mainly moderate rain (cross-hatched) and showers (symbols). Beneath each of the actual charts are the 24-hour and 36-hour prognostic charts which verify at that time. On these, the forecast rainfall is shown at each grid point by symbols (+, ○, ■) which distinguish slight, moderate and heavy rates of rain respectively. In order to keep the patterns of the main frontal rain belts as clear as possible, forecast occurrences of very slight rain (less than 0.1 mm/h) have been omitted.

Verification time	Forecast chart	Comments	Assessment letter
		(*Charts on Figure* 1)	
00 GMT 12/6/73	T+36	The rain area over Scotland is too far south, but this is not a misleading forcast. The main fault is the weakness of the pressure gradients.	B
	T+24	The rain in Scotland is well placed and the intensity seems about right.	A
12 GMT 12/6/73	T+36	The cold front is correctly placed over Ireland and the extensive area of moderate rain over northern Scotland is quite realistic.	A

Verification time	Forecast chart	Comments	Assessment letter
00 GMT 13/6/73	T+24	The intensity of the narrow, weakening cold front is well forecast but it is a little slow, being about 1 grid length too far north. No convection over Ireland was forecast.	B
12 GMT 13/6/73	T+36	On both these forecasts the pressure trough over north-west Europe has been moved too slowly, but the rapid stabilization of the air over the British Isles and transition from cyclonic to anticyclonic curvature of the isobars, coupled with the absence of any rain, was well forecast.	A
	T+24		A
		(*Charts on Figure* 2)	
00 GMT 19/6/73	T+36	The forecast rainfall pattern suggests an active warm front over north-east Scotland and a weaker cold front over western Ireland. The cold front is too slow by at least 1 grid length, but is not totally misleading, for rain is forecast over Ireland as far south as 52°N.	C
	T+24	The location and intensity of the cold front rain are very well forecast.	A
12 GMT 19/6/73	T+36	The frontal rain is well placed over eastern Scotland but is some 2 grid lengths misplaced over southern England.	B
	T+24	Apart from the premature clearance of rain in eastern Scotland, this forecast is good.	A
00 GMT 20/6/73	T+36	The forecasts for this particular time are not in fact too badly astray, but this is a lucky chance. The model is not getting the full extent of the low pressure development over Belgium and there is no warning of the possible spread back of the rain from the North Sea into eastern England.	B
	T+24		B
12 GMT 20/6/73	T+36	These are incorrect and misleading forecasts. The model moves the rain trough slowly but steadily east—whereas the developing Belgian low remains stationary and its circulation brings extensive moderate or heavy rain back over a great part of the British Isles.	D
	T+24		D
		(*Charts on Figure* 3)	
00 GMT 27/6/73	T+36	With the development of a pressure trough in about the right place and some isolated grid points giving rain, this forecast gets the correct 'weather type', but has only the poorest indication of the details.	C
	T+24	The location of the rain area over south-east England is remarkably good, though the intensity was under-forecast. The general line of the warm front in the English Channel and Biscay is discernible, though too far south.	B
12 GMT 27/6/73	T+36	Not a very convincing forecast chart, although ill-defined pressure patterns are typical of this weather type. The forecast rain areas bear little relation to reality.	D
	T+24	A substantial rain area over Brittany is forecast, about 1 grid length too far south.	B

Verification time	Forecast chart	Comments	Assessment letter
00 GMT 28/6/73	T+36	A remarkably good forecast, over both England and France, of the location of the frontal rain areas. The intensity over England is too weak.	A
	T+24	The northern boundary of the rain over England is about 1 grid length too far south, but otherwise this looks a good forecast for England. Over France the cold front movement is too slow.	B
12 GMT 28/6/73	T+36	Both these forecasts are quite good. Over England the location and intensity of the trailing rain area is well-handled, with the T+24 forecast being marginally more correct.	B
	T+24		A
		(*Charts on Figure* 4)	
00 GMT 1/7/73	T+36	Quite a good forecast with some development of rain occurring in the pressure weakness to the south-west of Ireland. Over Scotland the cold front is not clearly forecast, but over southern Ireland it is quite well placed.	B
	T+24	An unimpressive forecast. No specific developments are forecast in the area south-west of Ireland and the frontal rainfall is too weak and disorganised to give any useful guidance.	C
12 GMT 1/7/73	T+36	Although the rain on this front progressively decreases, the complete lack of any significant rain at this stage is too premature a forecast.	C
	T+24	The ill-defined rain belt appears to be well placed but it is too weak, especially over the high ground of Scotland.	B
00 GMT 2/7/73	T+36	Another forecast of a too rapid cessation to the rain. The positioning is fairly good.	B
	T+24	This has got right the general impression of patchy outbreaks of rain on the weakening front but details of the intensity and location are wrong.	B
12 GMT 2/7/73	T+36	Evidence from the North Sea is sparse, but this appears to be a good forecast.	A
	T+24	A correct forecast of dry weather over the British Isles, but it is likely that some rain is still falling over the North Sea and this should have been shown.	B

In these assessments, the letters have the following meanings:

Letter	General character of the the forecast chart	Forecast rain areas over the British Isles
A	Very good	Substantially correct in location and intensity
B	Good; gives useful forecast advice	Slight errors in either location or intensity
C	Fair, but not seriously misleading	Correct 'type'—but definite errors in both location and intensity
D	Poor	Major forecasting errors

Table I shows the frequency with which the various assessment letters occur on the four situations covered in this paper. The figures reflect a slight diminution in the overall usefulness of the prognoses as the forecast time increases from T+24 to T+36. But even at T+36 it is still possible to place two-thirds of the forecasts into categories A or B. At T+24 the proportion of such forecasts is higher, and the overall figure of the 23 out of 30 in categories A and B shows that at least 75 per cent of these individual forecast charts gave good, useful forecast advice.

TABLE I—ASSESSMENT OF THE SYNOPTIC VALUE OF THE FORECAST CHARTS

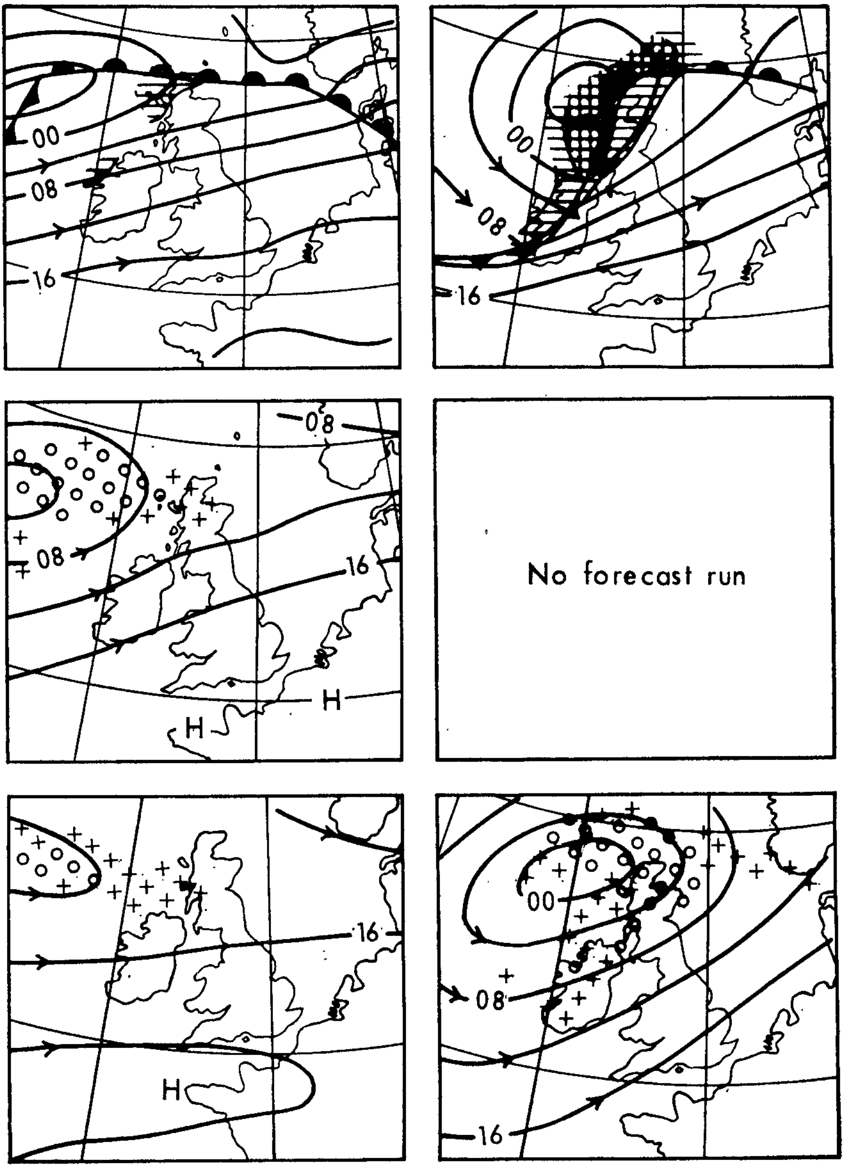
		Assessment letter				
		A	B	C	D	Total
Forecast chart	T+24	5	8	1	1	15
	T+36	4	6	3	2	15
Total		23		7		30

The quantitative rainfall forecasts. Figures 5–8 show, for each occasion, the actual and forecast accumulations of rain during the 'rainfall day' extending from 09 GMT on Day 1 to 09 GMT on Day 2. The forecast values are plotted, in millimetres, from an array of 72 grid points covering the area of the British Isles. They are values computed during the forecast runs based on 00 GMT data on Day 1, and are the predicted accumulations between the (T+09) and (T+33) hours of these forecasts.

The actual accumulations are the average areal rainfall amounts over 100-km squares centred on the model's grid-point locations. These values were produced by computer using the Comprehensive Areal Rainfall Program (CARP)[2] developed by the Agriculture and Hydrometeorology Branch of the Meteorological Office, in which an analysis is made of the daily rainfall totals from over 6000 rain-gauges covering England, Scotland and Wales. Since no measurements are available over the sea, the only grid squares for which reliable estimates of the actual accumulations can be made are those which lie entirely, or very largely, over land. There are only 17 such grid squares.

There can be little doubt that in the broadest terms these four situations were more or less correctly handled by the model. Figures 6 and 7 show the two occasions when wet weather was forecast for the south of the country, while Scotland remained dry; this proved to be correct. Figures 5 and 8 show the two occasions when the pattern was reversed; Scotland getting the rain while England remained dry. On these two occasions the forecasts were broadly correct, though Figure 8(b) is the least convincing of the four forecast charts.

However, when attention is transferred from the broad sweep of the synoptic-scale features discussed above, and is concentrated on individual grid points it is clear that a very different order of forecasting accuracy is attainable. A visual comparison of the forecast and actual values at corresponding grid points in Figures 5–8 is enough to convince one that the correlation is very small. Not only is the general level of the forecast rainfall below that of the actuals but there is also in each case an error in the location of the rain areas. These positional errors, though they may amount to only one or two grid lengths, are quite enough to produce large rainfall errors at individual grid points.



T+00

T+24

T+36

00 GMT

12 GMT

12 June 1973

FIGURE 1—THE SYNOPTIC SITUATION AT 00 AND 12 GMT ON 12–13 JUNE 1973 (T+00) TOGETHER WITH THE 24- AND 36-HOUR PROGNOSES WHICH VERIFY AT THOSE TIMES (T+24 AND T+36)

For explanation of the symbols see page 210.

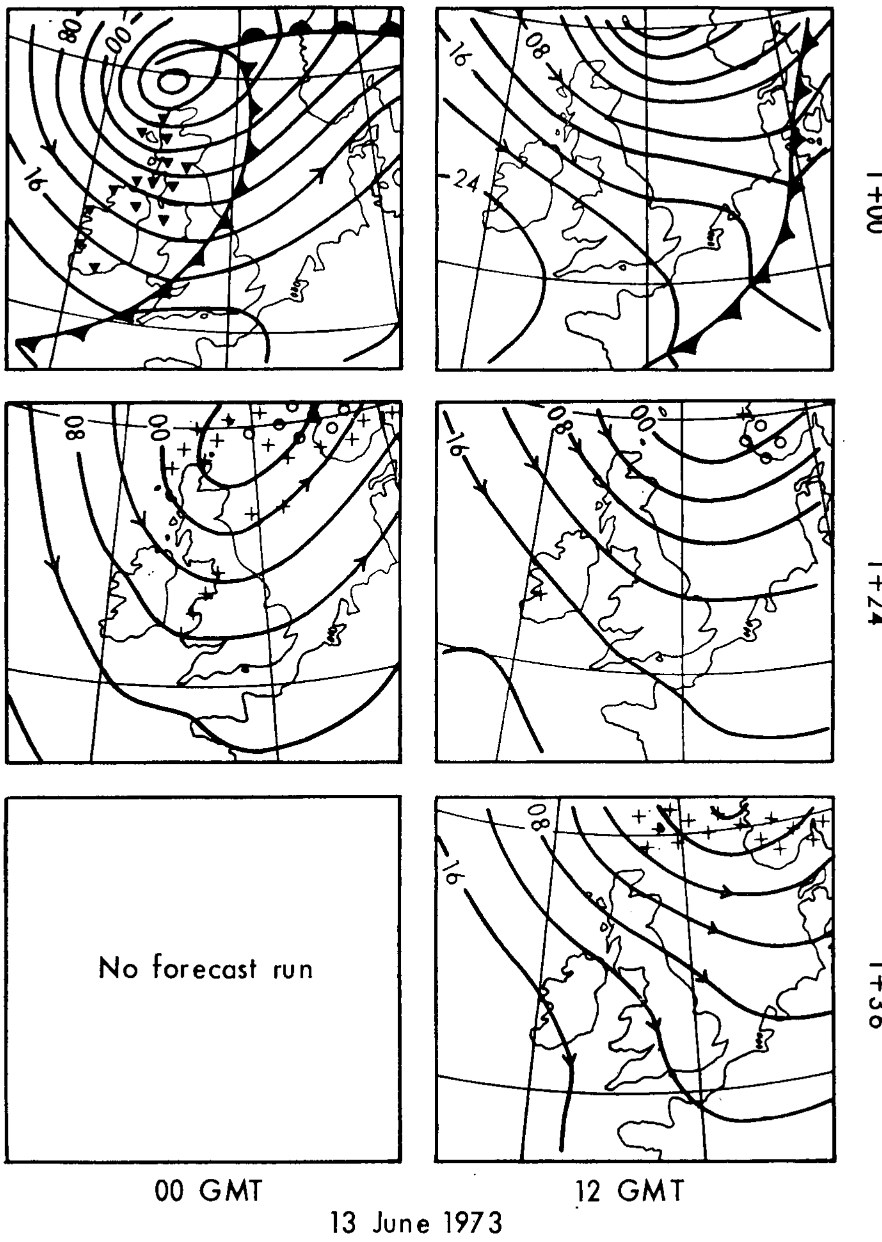


FIGURE 1 (*continued*)

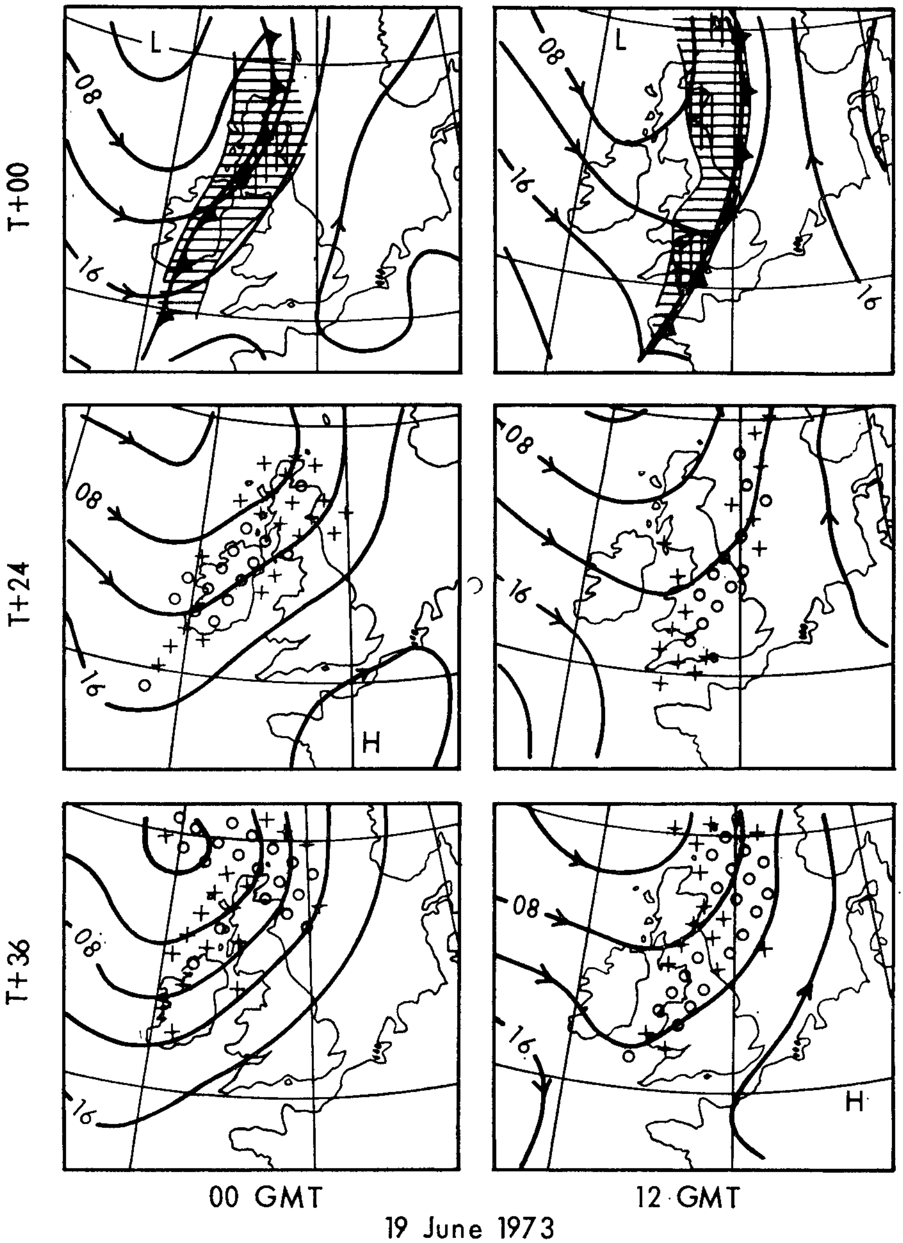


FIGURE 2—THE SYNOPTIC SITUATION AT 00 AND 12 GMT ON 19–20 JUNE 1973 (T+00) TOGETHER WITH THE 24- AND 36-HOUR PROGNOSES WHICH VERIFY AT THOSE TIMES (T+24 AND T+36)

For explanation of the symbols see page 210.

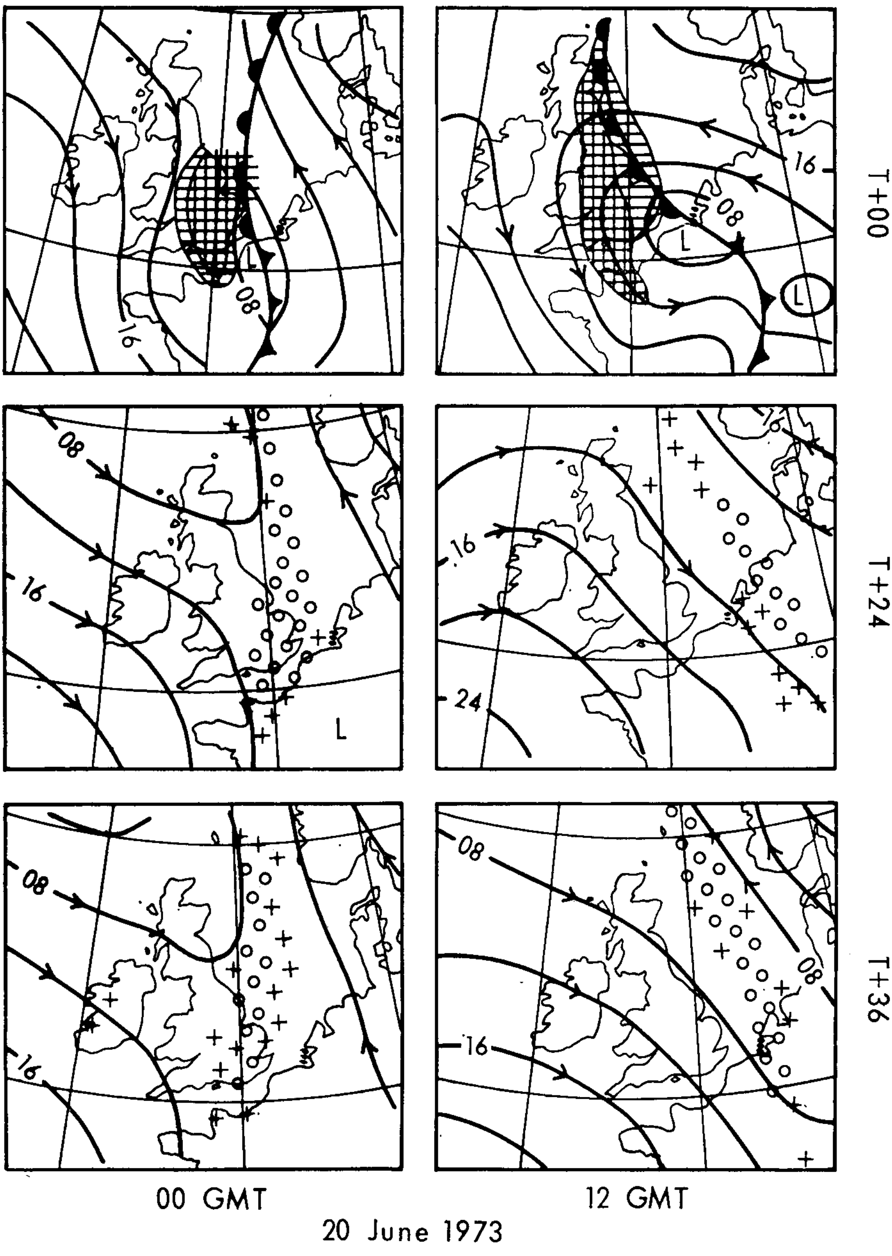


FIGURE 2 (*continued*)

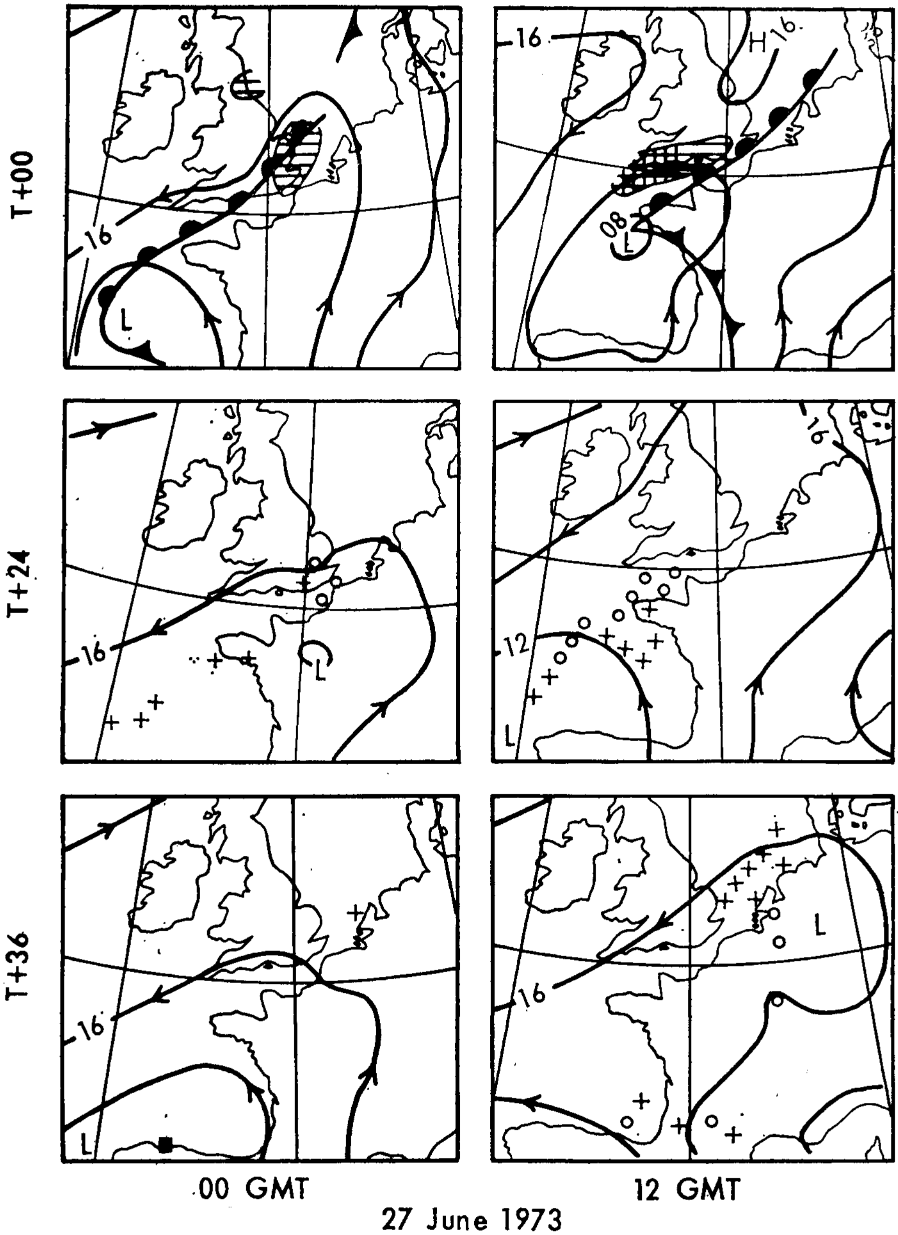
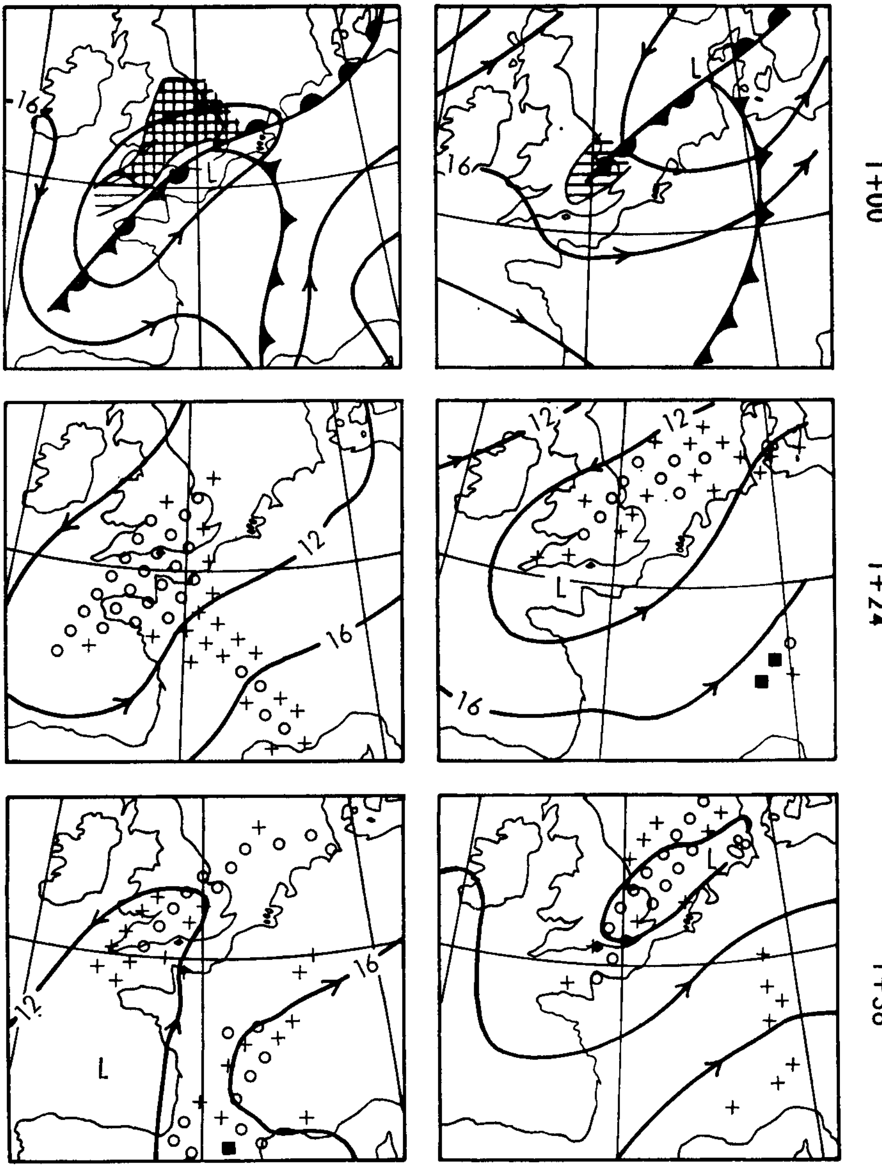


FIGURE 3—THE SYNOPTIC SITUATION AT 00 AND 12 GMT ON 27–28 JUNE 1973 (T+00) TOGETHER WITH THE 24- AND 36-HOUR PROGNOSES WHICH VERIFY AT THOSE TIMES (T+24 AND T+36)

For explanation of the symbols see page 210.



00 GMT 12 GMT

28 June 1973

FIGURE 3 (*continued*)

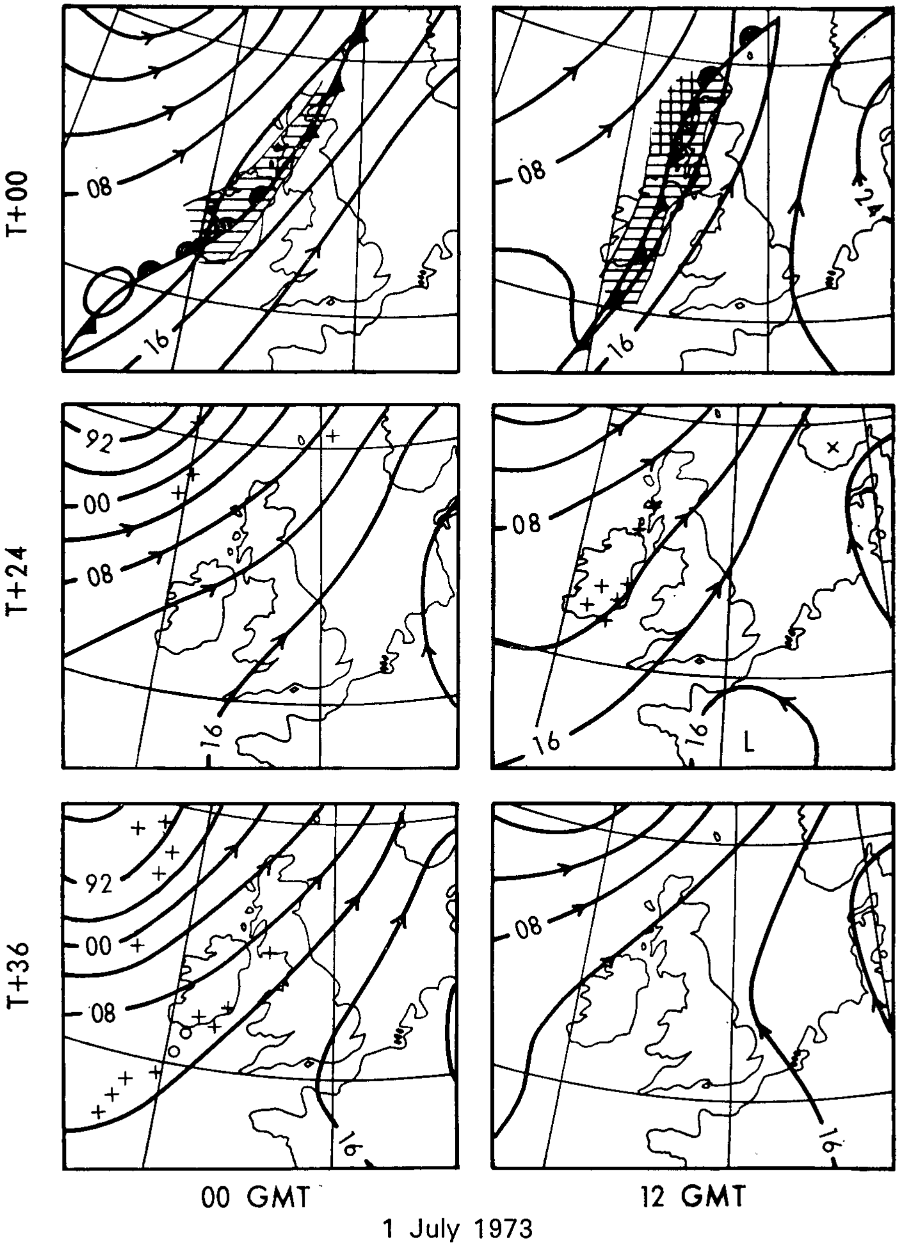


FIGURE 4—THE SYNOPTIC SITUATION AT 00 AND 12 GMT ON 1–2 JULY 1973 (T+00) TOGETHER WITH THE 24- AND 36-HOUR PROGNOSES WHICH VERIFY AT THOSE TIMES (T+24 AND T+36)

For explanation of the symbols see page 210.

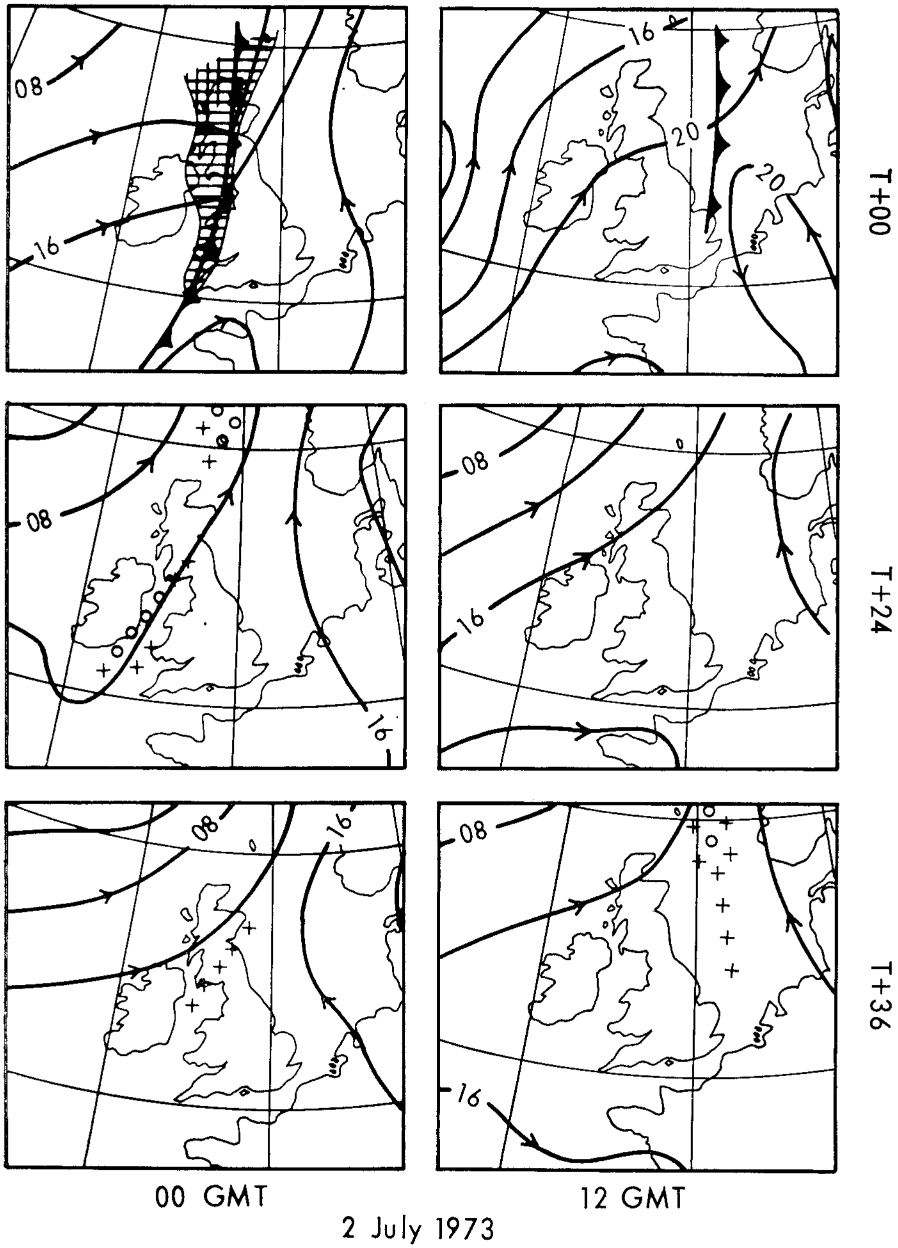


FIGURE 4 (*continued*)

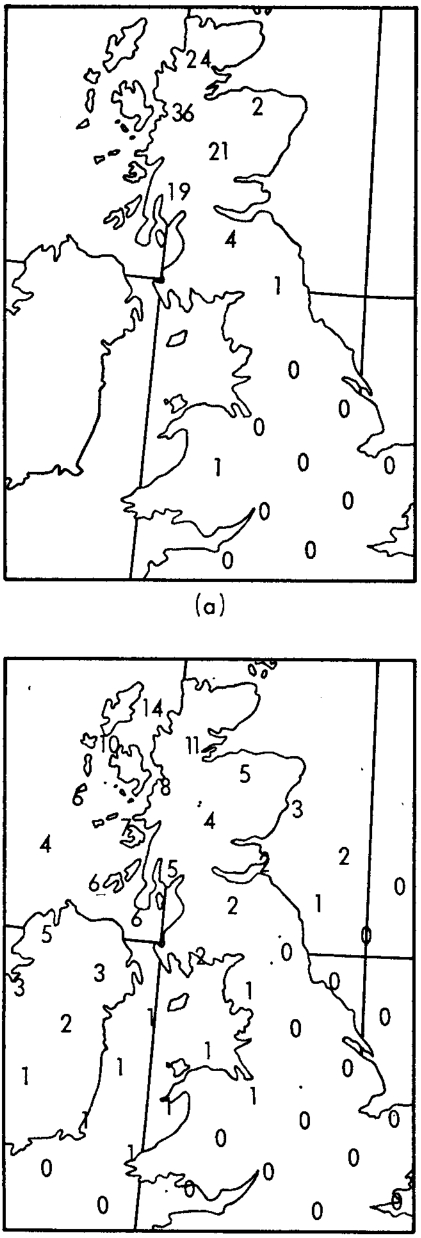


FIGURE 5—24-HOUR RAINFALL TOTALS FROM 09 GMT, 12 JUNE 1973

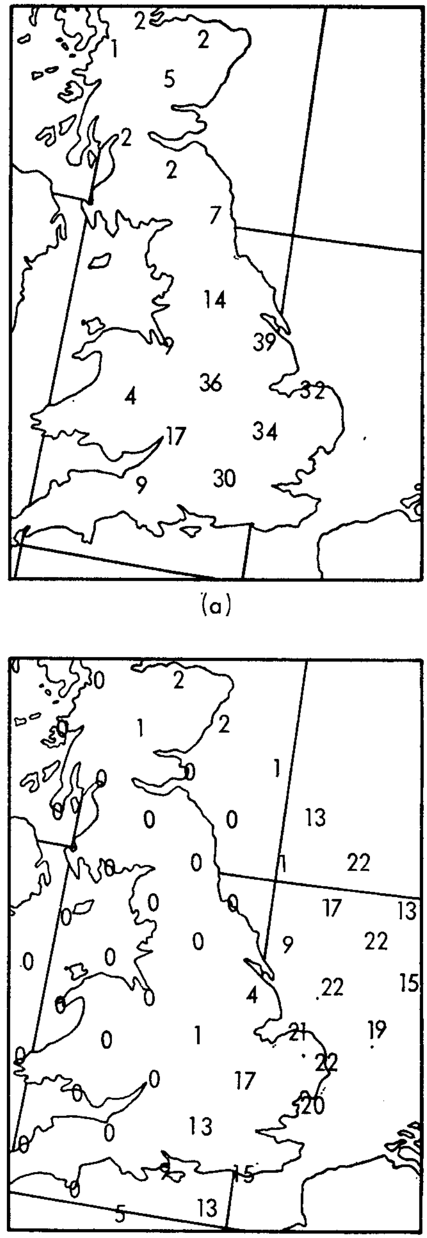
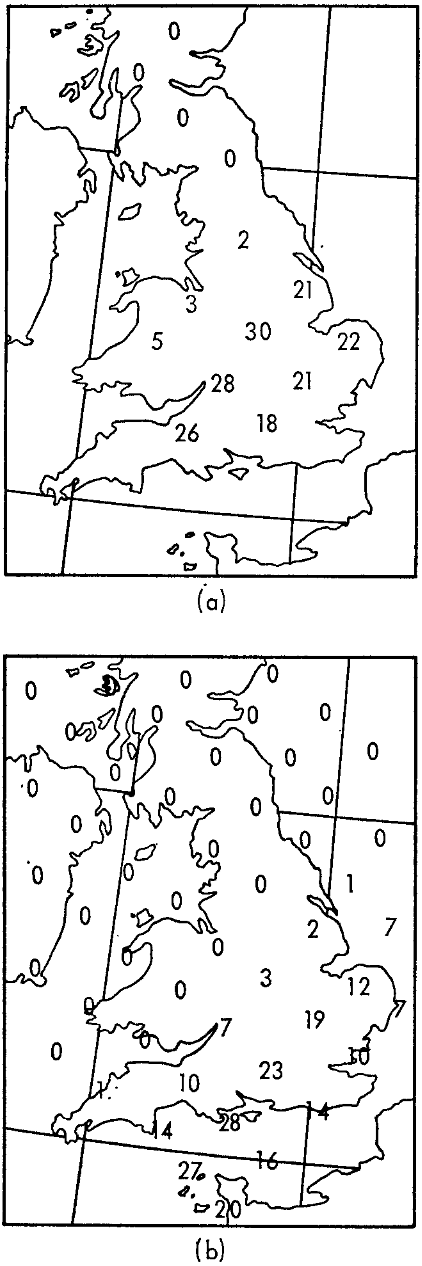


FIGURE 6—24-HOUR RAINFALL TOTALS FROM 09 GMT, 19 JUNE 1973

(a) Actual values (mm) averaged over 100-km squares
(b) Forecast values (mm) at grid points



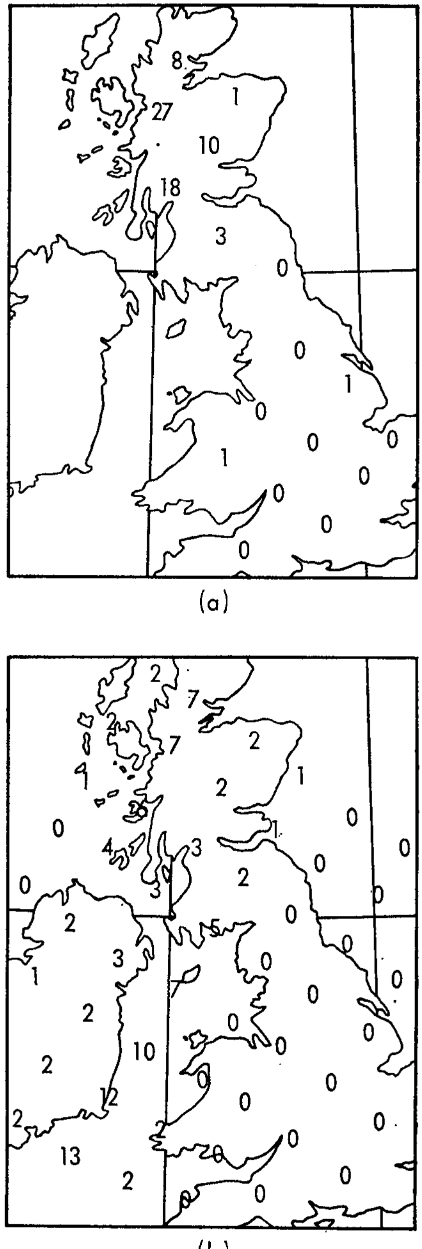


FIGURE 7—24-HOUR RAINFALL TOTALS FROM 09 GMT, 27 JUNE 1973

FIGURE 8—24-HOUR RAINFALL TOTALS FROM 09 GMT, 1 JULY 1973

(a) Actual values (mm) averaged over 100-km squares
(b) Forecast values (mm) at grid points

As far as it is possible to do so, with the limited information available on the actual charts, the most meaningful assessment of the value of Figures 5–8 is to list the errors occurring in the forecast location and magnitude of the maximum 24-hour rainfall total.

TABLE II—ERRORS OCCURRING IN THE FORECAST LOCATION AND MAGNITUDE OF THE MAXIMUM 24-HOUR RAINFALL TOTAL

Figure	Date	Highest rainfall at a grid point		Approx. distance between forecast and actual maxima
		Actual	Forecast	
		mm		*km*
5	12/6/73	36	14	140
6	19/6/73	39	22	180
7	27/6/73	30	28	220
8	1/7/73	27	7	50
	Mean values	33	18	150

Conclusions. The results show that, on the current performance of the 10-level model, the synoptic value of the rainfall forecasts is considerable. But as regards quantitative forecasting on the scale of one grid length the forecasts are of lower reliability. Errors in location of forecast rain areas are frequently about one or two grid lengths and the quantity of rain forecast by the model is generally only one-half to two-thirds of the actual values.

The reasons for particular forecasting errors are often quite difficult to pin-point with certainty. Sometimes an obvious fault can be traced, but usually it is the complex result of a number of factors whose effects are interrelated. At times there may be a lack of initial data, or there may be slight errors in the analysis of some crucial observations, or in their quality control. There are errors due to the approximations which have to be made when using finite difference methods to solve the mathematical forecasting equations. And there are errors due to the fact that most of the physical processes which occur in the real atmosphere are only modelled in an incomplete and approximate way in the computer programs. Some obvious indications of this are apparent in the charts displayed here, where the lack of a sufficiently detailed representation of topography in the model leads to serious underestimates of the rainfall over Scotland. It is also clear from the rainfall totals that the convective rainfall in the current formulation of the model is not sufficiently realistic.

The four actual charts in Figures 5–8 show that, even in these quite average frontal situations, rainfall gradients of over 1 inch (per rainfall day) per 100 km are not infrequent. With actual gradients of this magnitude it is clear that the misplacement of a rain belt by as little as one grid length on a forecast chart can result in large errors at some grid points. The achievement of high accuracy and reliability at this level of spatial resolution is a very formidable task.

REFERENCES

1. BENWELL, G. R. R., GADD, A. J., KEERS, J. F., TIMPSON, MARGARET S. and WHITE, P. W.; The Bushby-Timpson 10-level model on a fine mesh. *Scient Pap, Met Off, London*, No. 32, 1971.

2. SALTER, PAULINE M.; Areal rainfall analysis by computer. Geneva, World Meteorological Organization. Distribution of precipitation in mountainous areas, Vol. II, Geneva, 1972, pp. 497–509.

551.589.1(53)

WINTER AND SPRING WEATHER AT RIYADH, SAUDI ARABIA

By D. E. PEDGLEY
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Summary. The influence of synoptic-scale disturbances on the winter and spring weather at Riyadh is discussed with the help of seven examples from 1972. Hourly observations from the synoptic network in Saudi Arabia are used, together with surface and 500-mb charts and vertical time-section winds for 12 GMT. Small cyclonic circulations form over north-western Saudi Arabia and move east or south-east to the Persian Gulf. These cyclones either form on a cold front or a front develops within about one day. Heavy showers can occur when low-level moisture is advected either by southerly winds ahead of a cold front or by easterlies around the northern side of a centre.

Introduction. Little has been written about the synoptic meteorology of Saudi Arabia. Kuo,[1] in a general account, describes the dominance of southward-extending ridges of high pressure in the winter, interrupted by depressions moving eastward from the Mediterranean. Associated cold fronts, sometimes with rain or even thunder, become diffused as they cross the country; they are preceded by south-east winds (Arabic: *kaus*) and followed by north-westerlies (*shamal*), which in the east can be strong enough to give duststorms. Studies of individual rainy spells, in the east at Sharjah[2] and in the west at Jiddah,[3] have shown the influence of developments in the upper troposphere on surface disturbances.

Until recently, the nature of synoptic disturbances over Saudi Arabia has been poorly understood, but the growing network of observing stations (Figure 1) now makes it possible to examine the disturbances more closely.

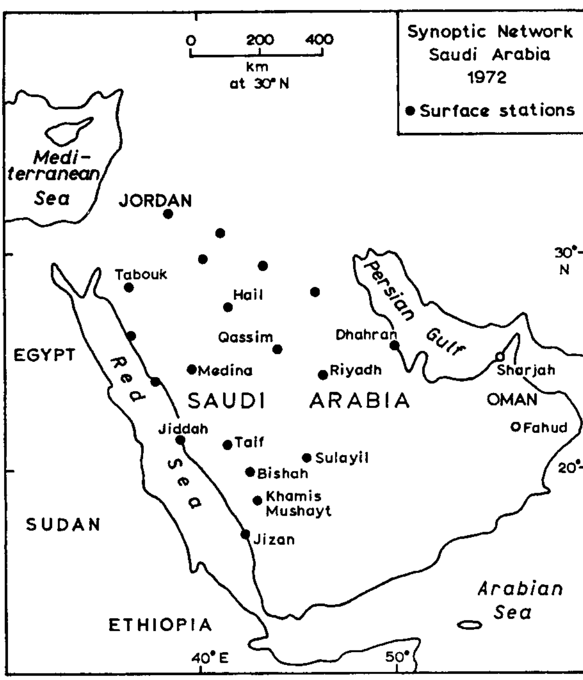

FIGURE 1—SYNOPTIC NETWORK IN SAUDI ARABIA AND OTHER PLACES MENTIONED IN THE TEXT

This paper describes some examples from the winter and spring of 1972, particularly their influence on the weather at the capital city, Riyadh (25°N 47°E).

Day-to-day changes. Time sequences of 12 GMT (1500 local time) observations at Riyadh show oscillations in pressure, wind and temperature with a periodicity of 2–8 days. In general, falling pressure is associated with rising temperatures and south-east winds, whereas rising pressure is associated with falling temperatures and north-west winds. A change from the former to the latter is sometimes sudden and resembles the passage of a cold front. On other occasions the change is more gradual, as though a cyclonic centre were passing nearby; south-east winds then either veer through south-west to north-west, or they back through north-east. Sometimes there is a spell of light and variable winds lasting a few hours. The reverse change, from north-west to south-east, is nearly always gradual, and is a veer through north-east, i.e. anticyclonic centres or associated ridges pass eastwards to the north of Riyadh.

The surface disturbances resembling cold fronts occur ahead of troughs in the upper westerly winds. Middle and high clouds are common, and sometimes there is occasional rain. High stratocumulus may accompany these clouds, but cumulus develops on days when there is a lower tropospheric inflow of moisture. Dew-points may then rise to 10°C, or even 15°C in spring. When south-east winds first develop as pressure starts to fall after a strong rise, dew-points are typically +5° to —5°C and low clouds are rare. Near pressure minima, where both dew-points and temperatures are usually above average, cumulonimbus clouds can develop, especially in the late afternoon, and lightning can occur well into the night. Thunderstorms are most likely between dusk and midnight, with squalls, sudden temperature falls and pressure rises, and sometimes duststorms.

High dew-points can persist for about a day after winds have changed to northerly, but with a good rise of pressure and persistent northerly winds dew-points fall to 0° to —5°C.

The following examples illustrate the nature of disturbances affecting the weather at Riyadh. Emphasis is placed on time sequences of hourly observations, and on 12 GMT surface synoptic charts, but some idea of structure aloft can be obtained from changes in upper winds shown by vertical time-sections based on soundings at 00 and 12 GMT, and the deductions were checked by using 500-mb synoptic charts based on routine 12 GMT data.

11 *January* 1972. Surface synoptic charts showed that a depression moved east-south-eastwards to the north of Riyadh (Figure 2). A cold front passed between 15 and 16 GMT, with a wind veer from 200° 15 kt to 330° 20 kt and a temperature fall from 22° to 18°C; there was blowing dust from 11 to 19 GMT. The depression centre had moved north of Hail and Qassim, where the cold front passed soon after 13 GMT on the 10th and 06 GMT on the 11th respectively, and later it was overhead at Dhahran from 19 to 23 GMT on the 11th. The cold front was not clear-cut at Medina or Taif, but north to north-east winds set in at Sulayil during the night of 11th/12th (no observations were made there in 1972 between 18 and 05 GMT). Over the Red Sea, there was a weak push of north-westerlies to southward of Jiddah, and there was no evidence for the front reaching Fahud in the interior of Oman, where winds persisted from the south and south-east. Ahead of the front, large cumulus clouds had developed by

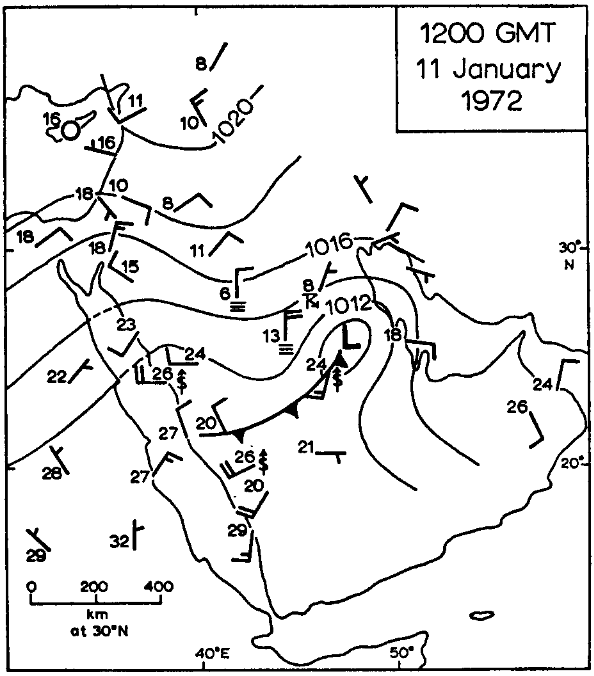

FIGURE 2—SURFACE CHART FOR 12 GMT ON 11 JANUARY 1972
Symbols show weather at 12 GMT or during the previous six hours.

12 GMT on the western escarpment, and there was some shallow cumulus or stratocumulus in the northerlies. A band of middle-level clouds lay north of Riyadh at 12 GMT, later giving 0.1 mm of rain there between 1605 and 1830 GMT.

The vertical time-section (Figure 3) showed the greatest changes in wind direction were confined to below 700 mb. Above that level, westerlies increased in speed with height, and direction changes suggested the eastward passage of a weak trough, its axis passing Riyadh early on the 12th. On the 500-mb charts, the axis was found to move from about 40°E at 12 GMT on the 11th to about 50°E on the next day. This trough was cold cored, temperatures at Riyadh being about 3 degC below those two days before and two days after at all levels to at least 200 mb.

29 *January* 1972. Again a depression moved east-south-eastwards to the north of Riyadh; it travelled at 35 kt and maintained a central pressure of about 1009 mb. After a short calm spell, winds picked up from the west between 07 and 08 GMT, becoming north-west at 20–35 kt after 10 GMT. The centre had moved over Hail between 18 and 21 GMT on the 28th and later cleared Dhahran by 09 GMT on the 29th. Its cold front passed Qassim 01–02 GMT on the 29th, and Taif 03–04 GMT, when westerlies changed to easterlies. Easterlies also set in at Sulayil between 17 and 18 GMT, and the front passed Fahud between 08 and 09 GMT on the 30th, where it was followed by north to north-west winds gusting to 30 kt. The front did not reach Khamis Mushayt.

On the 28th there was much middle-level cloud to the west and north of Riyadh, with outbreaks of rain which reached Riyadh during the night giving

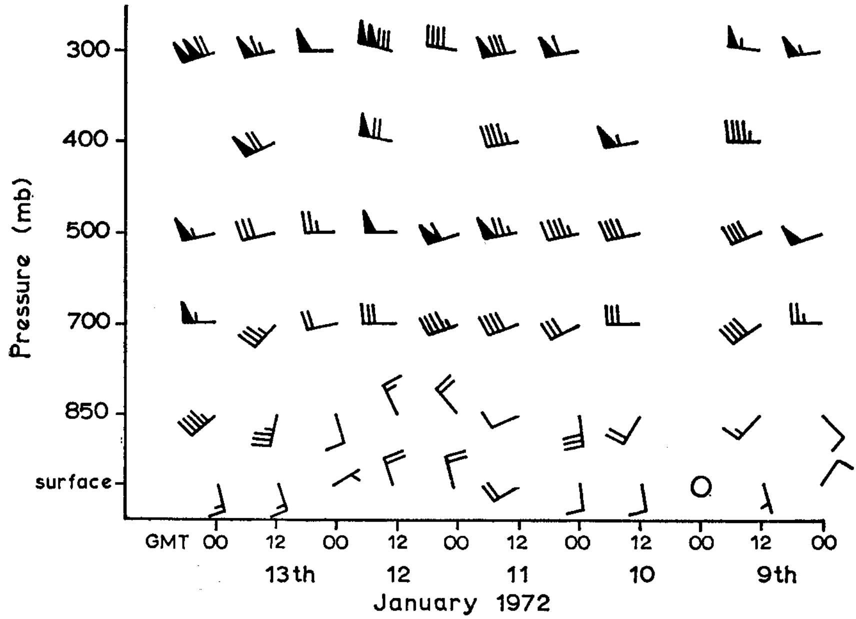

FIGURE 3—VERTICAL TIME-SECTION SHOWING WINDS AT RIYADH, 9–13 JANUARY 1972

a fall of 10 mm, accompanied by a thunderstorm. Dew-points there were 10–12°C, and the moist air almost certainly came from the Persian Gulf. The 12 GMT synoptic chart showed similar dew-points behind the depression, but falling quickly to about 0°C over the north-west of the country. The vertical time-section again showed greatest changes in wind direction were below 700 mb, where temperature falls of 7 degC occurred. A cyclonic centre at 500 mb moved quickly eastwards at about 33°N — from 35°E on the 28th to 47°E on the 29th (i.e. at 50 km/h), accompanied by a trough lying north-east to south-west that crossed Riyadh early on the 31st. Thus, the surface depression lay ahead of the upper trough; the trough axis crossed Riyadh nearly two days after the surface front.

12 *February* 1972. An anticyclone moved east-south-eastwards over north-east Arabia, maintaining a central pressure of about 1024 mb. The clear, calm night gave a minimum temperature near 0°C at Riyadh. At 12 GMT, south-east winds covered most of the country (Figure 4), with dew-points 0° to —5°C, but 9°C at Dhahran where evaporation from the Persian Gulf had probably produced a shallow moist layer of air. There was no low cloud in the interior, but cumulus and stratocumulus were present over the Red Sea coast and adjacent scarp in moist southerly winds that spilled on to the plateau as south-westerlies, contrasting strongly with air over the interior. A depression forming over the north-west of the country moved east-south-east at 10 kt in the following 24 hours. Ahead of its cold front moist westerly winds spread from the Red Sea to allow cumulus clouds to develop in the north-west.

The anticyclone lay beneath north-west winds ahead of a large-amplitude upper ridge, weakening as it moved east, and associated with only small changes in temperature.

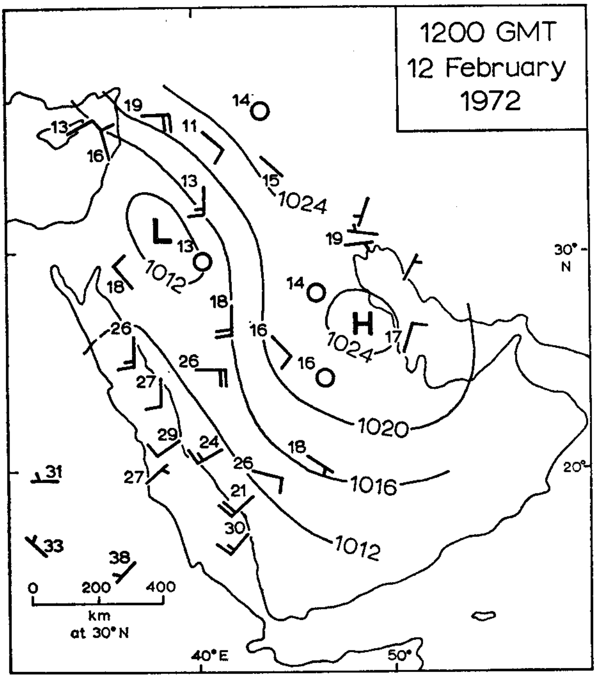

FIGURE 4—SURFACE CHART FOR 12 GMT ON 12 FEBRUARY 1972

19 *February* 1972. A depression moved eastwards to the north of Riyadh (Figure 5), with its cold front passing between 10 and 11 GMT, when winds veered from south to west, and then to north by 14 GMT. The centre had moved south of both Hail and Qassim and was over Dhahran by 14 GMT. Northerlies reached Sulayil during the following night, and north-easterlies reached Bishah although south-westerlies persisted at Khamis Mushayt. Dew-points at Riyadh were about 9°C in the northerlies but fell to near 0°C next day. Thus, moisture was advected from the Persian Gulf round the northern side of the depression, and it was associated with small cumulus and stratocumulus clouds.

Winds aloft suggested the passage of a trough at all levels up to at least 300 mb, crossing Riyadh at 500 mb during the latter half of the 20th, and with temperature falls of 10 degC in two days at 850 mb, decreasing upwards to about 3 degC at 300 mb; 500-mb charts showed that this trough had a large amplitude and was inclined from north-east to south-west.

22 *March* 1972. A cold front moved slowly south-eastwards towards Riyadh from 20 to 22 March (Figure 6). It was preceded by moist southerly winds with dew-points of 10–15°C, and followed by westerlies with dew-points about 0°C. Cumulus and cumulonimbus developed along and ahead of this front with much middle-level cloud giving outbreaks of rain, thunderstorms and dust-storms. Wind and temperature changes were erratic, presumably caused by downdraughts from the storms. Lightning was seen at Riyadh on the night of 20th/21st, and occasional rain on the 21st amounting to 17 mm was followed by

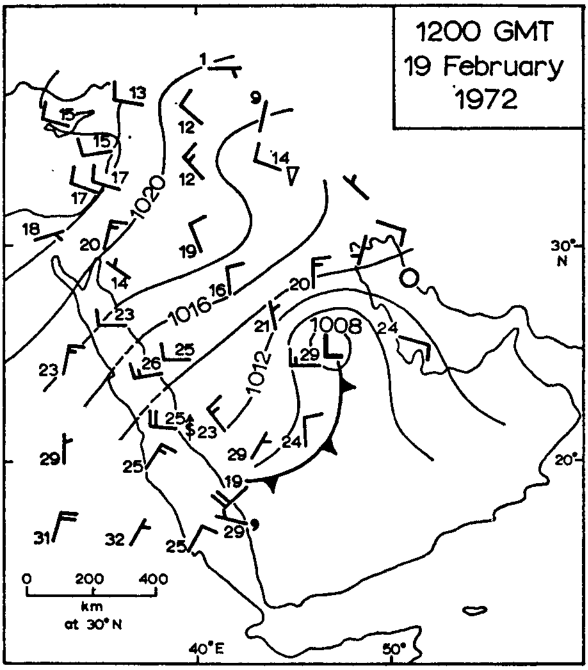

FIGURE 5—SURFACE CHART FOR 12 GMT ON 19 FEBRUARY 1972
Symbols show weather at 12 GMT or during the previous six hours.

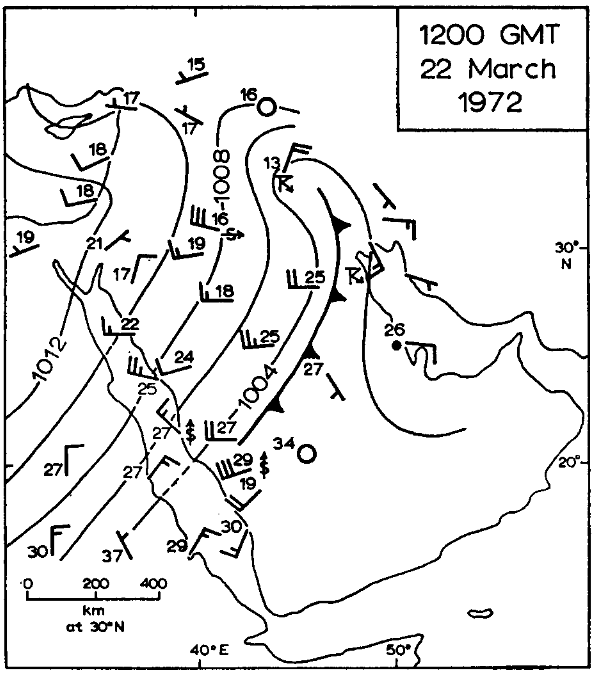

FIGURE 6—SURFACE CHART FOR 12 GMT ON 22 MARCH 1972
Symbols show weather at 12 GMT or during the previous six hours.

further night-time lightning. From 1610 to 1830 GMT on the 22nd there was a thunderstorm with hail and a squall, and rainfall totalled 50 mm. A sudden fall of temperature from 23° to 16°C occurred. It is not possible to say if this storm formed on or somewhat ahead of the cold front. The lower tropospheric moisture probably came from the south-west, i.e. the Red Sea, but some may have come from the south-east, i.e. the Arabian Sea, judging by dew-points above 10°C at Sulayil.

As pressure built quickly to the north, an anticyclone (central pressure 1014 mb) developed over the north-east of the country by 12 GMT on the 23rd, resulting in north-east winds in the east and south-east winds in the west. As a result, the front accelerated eastwards across the Persian Gulf, although south-west winds persisted in the south-west, and moist air continued to flow over Riyadh from the Persian Gulf, even reaching Qassim on the 24th.

This interesting disturbance was accompanied by strong south-west winds in the middle and upper troposphere (Figure 7), but the greatest changes in direction were again below 700 mb. A large-amplitude trough was slow moving near 35°E from the 21st to 23rd, giving persistent south-west upper winds over the whole of Saudi Arabia. At 200 mb, the axis of the subtropical jet stream formed a sinusoidal pattern: a ridge over Algeria (27°N 6°E), a trough over Egypt (22°N 35°E) and a ridge over central Asia (41°N 70°E). Thus, Riyadh lay close to the southern side of the axis, and to the east of a stationary trough, i.e. in a region where strong upper divergence is to be expected. This divergence, together with a combination of surface heating and a lower tropospheric inflow of moist air, seems to have resulted in deep convection and the development of a severe storm at Riyadh. The synoptic pattern was similar to those where the subtropical jet stream is associated with severe storms elsewhere in the world. Moreover, thunderstorms were also reported in Mauritania on the 22nd in a similar stiuation, but ahead of the upstream trough — also slow-moving — off the north-west coast of Africa.

1 *May* 1972. A well-marked cold front moved south-east across Riyadh at 1225 GMT, with a temperature fall from 36° to 30°C between 12 and 13 GMT,

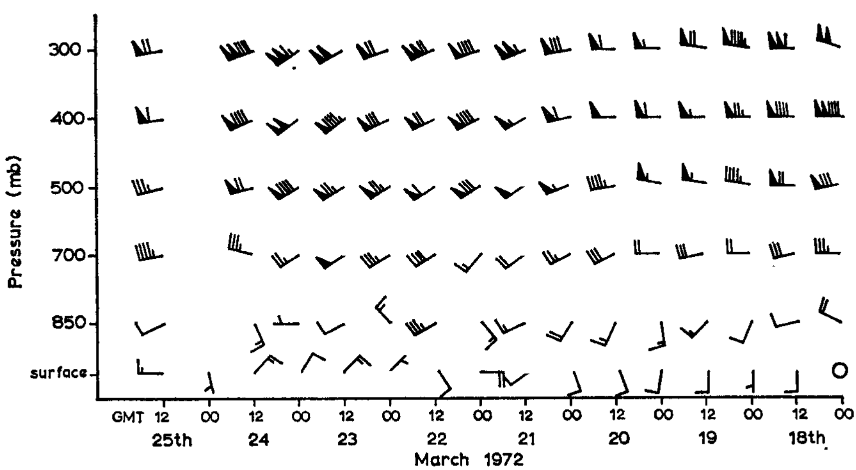

FIGURE 7—VERTICAL TIME-SECTION SHOWING WINDS AT RIYADH, 18–25 MARCH 1972

accompanied by a short spell of blowing dust as the wind veered from west-south-west to west-north-west. This front had crossed Tabouk on the night of the 29th/30th, Hail between 16 and 17 GMT on the 30th, and Qassim between 03 and 04 GMT on the 1st. By then there was some evidence for the formation of a new low-pressure centre, which moved east-south-east at about 20 kt to cross Dhahran at 22 GMT. Prefrontal south-west winds at Riyadh brought dew-points of 12–14°C from the Red Sea, accompanied by cumulonimbus clouds but no rain, although there was lightning in the evening. Dew-points rose to 15–17°C behind the front, probably as a result of advection around the north side of the developing depression, but they fell towards 0°C early on the 2nd.

The front was associated with a deep depression over the eastern Mediterranean. On the 29th, the front was lying from Jordan to south-eastern Egypt (Figure 8); ahead of it south to south-east winds covered most of Saudi Arabia with duststorms in the northwest, where moist air from the Red Sea brought dew-points around 10°C and widespread cumulonimbus, which was also present over high ground in the south-west. Surface north-west winds behind the front pushed along the length of the Red Sea, reaching south of Jizan on the 1st (Figure 9). This vigorous cold front was associated with a cyclone at 500 mb that moved from the eastern Mediterranean on the 29th to the Black Sea on the 2nd, with its accompanying trough in the westerlies crossing Riyadh late on the 2nd, i.e. nearly a day and a half after the surface front. Temperatures fell by 10 degC in 24 hours at 850 mb, but 5 degC at 700 mb and less at higher levels.

29 *May* 1972. A cold front moved south-eastwards across Riyadh between 09 and 10 GMT, when the wind veered from south to west-north-west and decreased in speed. Dew-points rose from 0°C to about 8°C, but temperature changes were little different from those expected in a diurnal variation. The front had passed Hail between 11 and 12 GMT on the 27th, and Qassim between 19 and 20 GMT on the same day, by which time there was again some evidence for the formation of a new low-pressure centre, moving east at 10 kt, reaching Dhahran by 18 GMT on the 29th. At Dhahran the temperature reached as high as 47°C at 12 GMT (Figure 10), when the wind direction was off shore. Only small cumulus clouds formed near the centre of this depression, but again there was cumulonimbus over the mountains of the south-west.

A short-wave trough at 500 mb moved eastwards across Riyadh early on the 30th but weakened as another trough developed over Egypt in association with a slow-moving cyclone over south-west Turkey. A temperature fall of 5 degC occurred at 850 mb, but changes were small at higher levels.

Conclusions. These few examples show that surface pressure troughs, with associated changes of wind from generally south-east to north-west, cross Riyadh some one to two days ahead of the axes of eastward-moving troughs in the middle- and upper-tropospheric westerlies. This vertical structure, together with the periodicity of 2–8 days, closely resembles the structure of springtime disturbances over north-east Africa.[4] Like the latter, the Arabian disturbances are of two principal types:

(a) cold fronts that have moved into the country from further west;

(b) small cyclonic circulations that form over the north-west of the country, subsequently moving east or south-east at 5–15° longitude per day.

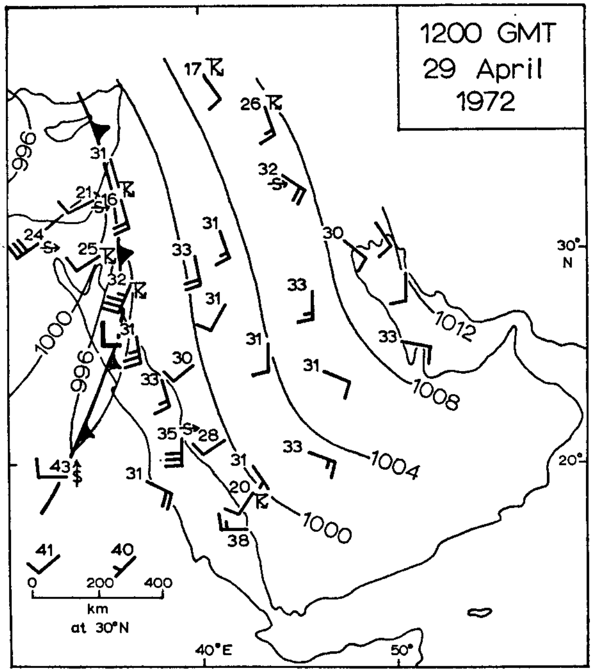

FIGURE 8—SURFACE CHART FOR 12 GMT ON 29 APRIL 1972
Symbols show weather at 12 GMT or during the previous six hours.

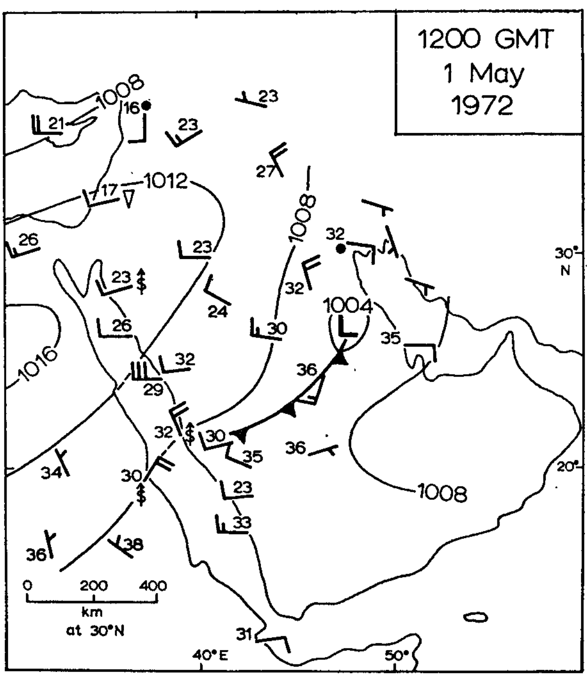

FIGURE 9—SURFACE CHART FOR 12 GMT ON 1 MAY 1972
Symbols show weather at 12 GMT or during the previous six hours.

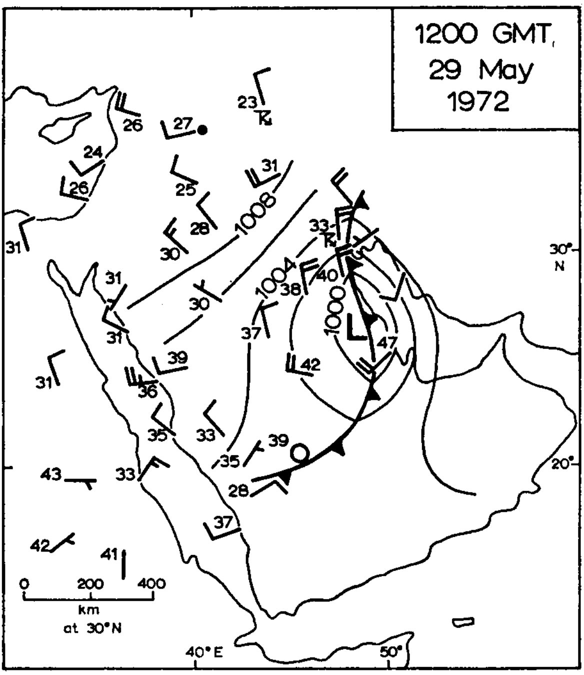

FIGURE 10—SURFACE CHART FOR 12 GMT ON 29 MAY 1972
Symbols show weather at 12 GMT or during the previous six hours.

The cyclonic circulations can develop either on a cold front or independently, within a south-easterly airstream on the western side of a retreating surface ridge. In the latter situation a cold front tends to develop along the axis of the pressure trough after about a day's travel across the centre of the country. The reasons for a preferred origin over north-western Saudi Arabia can only be guessed at, but this is a region where the lower tropospheric thermal pattern frequently has a warm ridge, presumably because the otherwise undisturbed easterly winds (with a south–north temperature gradient) are topographically distorted to south-east (on the north-east side of the massive highland complex of south-west Arabia and Ethiopia) and to north-east (on the north-west side of the highlands). When upper divergence develops temporarily, e.g. ahead of an advancing trough in the westerlies, and especially on the south side of the subtropical jet-stream axis to the east of where it crosses the trough line, the accompanying surface convergence can be expected to distort further the lower tropospheric wind and temperature fields so that a cyclonic circulation develops. As a centre moves away eastwards it will not develop much because it enters a region where the lower tropospheric temperature field is less favourable. The subsequent fate of these disturbances has not been examined.

Upper tropospheric divergence can also be related to the occurrence of middle- and high-level clouds, sometimes extensive and with occasional rain. Cumulus clouds develop where there is a sufficiently moist inflow in the lower troposphere, either:

(a) ahead of the cold front, from the south-east (Arabian Sea or Persian Gulf) or especially from the south-west (Red Sea); or

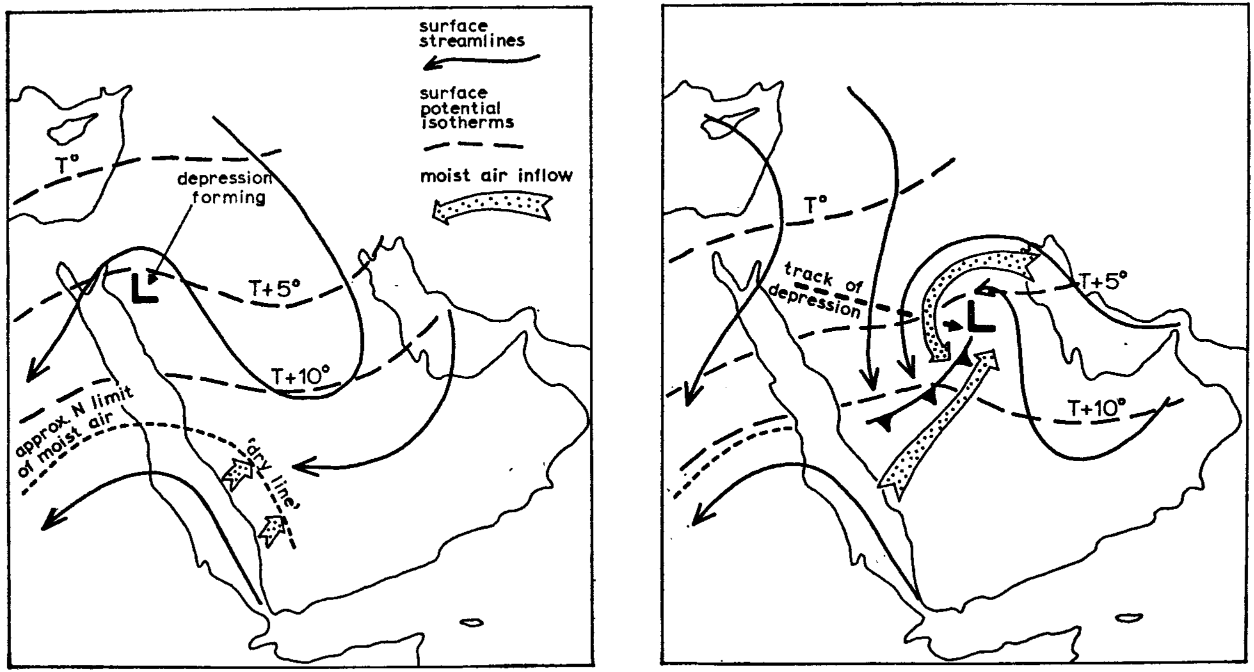

FIGURE 11—SCHEMATIC REPRESENTATION OF WIND AND ISOTHERM PATTERNS IN A DEPRESSION FORMING OVER NORTH-WESTERN SAUDI ARABIA AND MOVING EASTWARDS, SHOWING INFLOW OF MOIST AIR CONDUCIVE TO THE DEVELOPMENT OF CONVECTIVE LOW CLOUDS

(b) behind the cold front, from the north-east (i.e. from the Persian Gulf after passing around the northern side of the depression).

Southerly winds are frequently present over the southern Red Sea from October to May,[5] especially at 850 mb where they spill over the south-western plateau (e.g. at Khamis Mushayt) and are strongly contrasted with the usually much drier north-east to south-east winds of the interior (e.g. at Bishah and Sulayil). A 'dry line' can be visualized as being a quasi-permanent feature of this region. The southerlies are a source of moisture which can occasionally be drawn north-eastwards ahead of a cold front; on other days the moist southerlies appear to turn through east as they leave the Red Sea to flow south-westwards across the Sudan. These developments are shown schematically in Figure 11.

Acknowledgements. The research reported in this paper would not have been possible without the generous provision of data from original observation registers maintained by the Directorate-General of Meteorology in Jiddah, Saudi Arabia. The paper is presented with the permission of the Director, Centre for Overseas Pest Research, London.

REFERENCES

1. KUO, W. S.; A study of weather over the Arabian peninsula. *Met Bull, Taiwan Weath Bur, Taipei*, **11**, 1965, pp. 25–35 (translation available in the Meterological Office Library, Bracknell).
2. MURRAY, R. and COULTHARD, G. A.; A thunderstorm at Sharjah, Persian Gulf, on 23 November 1957. *Met Mag, London*, **89**, 1959, pp. 176–178.
3. PEDGLEY, D. E.; A heavy rainstorm over north-western Arabia. Boston, Mass., American Meteorological Society and World Meteorological Organization, Proceedings of the Symposium on Tropical Meteorology, June 2–11, 1970, University of Hawaii, Honolulu, 1970, p. E VII 1.
4. PEDGLEY, D. E.; Desert depressions over north-east Africa. *Met Mag, London*, **101**, 1972, pp. 228–244.
5. PEDGLEY, D. E.; The Red Sea convergence zone. *Weather, London*, **21**, 1966, pp. 350–358 and 394–406.

REVIEWS

Theory and applications of numerical analyses, by G. M. Phillips and P. J. Taylor, 225 mm × 150 mm, pp. x + 380, *illus.*, Academic Press Inc. (London) Ltd, 24–28 Oval Road, London, NW1 7DX, 1973. Price: £5.80 (hard cover), £3.90 (soft cover).

The authors have written the book as an introductory text on numerical analysis for undergraduate mathematicians, computer scientists, engineers and other scientists. The reviewer is not a professional teacher or lecturer and has studied the book from the point of view of a meteorologist whose particular line of work depends heavily on numerical analysis, and who has frequent recourse to information and instruction from such texts.

The great impetus given to numerical analysis by the advent of electronic computers has resulted in a rapid evolution of the subject. This has been most evident in research papers and has been difficult for textbook writers to keep up with. Nevertheless this book is modern in its approach without being encumbered by too much of the terminology of 'modern algebra'. Indeed the sentence 'We have included only a little on finite differences as they are not extensively used nowadays and are of little conceptual interest' may be regarded by many meteorologists as futuristic rather than modern.

It deals with the usual topics of interpolation, approximation, numerical differentiation and integration, solution of algebraic equations of one variable, systems of linear equations, systems of non-linear equations, ordinary differential equations, and boundary-value problems. Two notable omissions are sections on partial differential equations and eigenvalues. The omission of partial differential equations from a book of this scope is understandable as it is a very specialized topic. However, eigenvalues and eigenvectors are another matter, as they underlie so many applications, and so many of the difficulties which scientists encounter in the field of numerical analysis can be resolved by throwing the problem under examination into some canonical form, whereupon the nature of the difficulty is illuminated by a study of the eigenvalues of a matrix associated with the problem. An introductory text at this level should not leave its readers unaware of the power of such important tools as eigenvalues and eigenvectors. The topics dealt with are presented clearly and concisely and the text is well laid out, making the book easy to read and understand. In the chapter on 'best' approximation it is true, as stated, that of all the L_p approximations for $1<p<\infty$ the L_2 norm is the only one commonly used (i.e. least-squares approximation), but this does not justify the very scant treatment of the L_1 norm for approximation, especially in view of the very large volume of work on this topic over the past two decades and the advantages which the L_1 norm has with respect to erroneous data. It would have been appropriate to give the L_1 norm as much space as has been given to the L_∞ (minimax) approximation. There should also be much more on splines. Splines have been developed into a major interpolation and approximation tool over the past decade and deserve far more than two brief paragraphs. For students, for whom the whole book may be required reading, perhaps the index does not matter too much, but a working scientist will often use a book to try and get information on one specific topic *quickly*. For this a good subject index is needed. Most publishers seem to fail their customers here. A case in point with this book is that the sole reference to the L_1 approximation is given in the index as being on page 83. It is there all right, but another important property of the best L_1 approximation turns up on page 98. The text is well supplemented with examples for working, hints on solution, and, at the end of the book, the solutions themselves with, where necessary, brief remarks on how the solutions are obtained. Thus a reader should be able to consolidate his grip on the subject matter. The reviewer notes that the notation for problem 8.37 is not consistent with that of the foregoing chapter which follows the more customary usage of allowing the columns of the matrix to run through the domain-space whilst the rows run through the function-space.

To offset the above criticisms the book has two excellent features. First, it is a common experience these days that to reach some slight result in a research paper it is first necessary to wade through three or four pages of set-theoretical jargon in which the authors mainly establish that they have heard of mathematical rigour until finally one alights upon a result which could have been adequately proved on one page. Phillips and Taylor have included a chapter called 'Basic Analysis' which is a glossary of necessary terms with examples to drive the meanings home. Thus if you are apt to be put off by the statement that a certain theorem is true provided that f(x) satisfies a Lipschitz condition on [a, b,] Phillips and Taylor not only tell you what a Lipschitz condition is, they also make sure you understand it. Second, the Chapters 8 and 9 which introduce matrix/vector methods into the study of linear equations and the applications of matrix/vector norms will enrich the subject of numerical analysis for readers not already familiar with the power of this approach. In particular the authors are to be commended for their Chapter 9 which deals with matrix/vector norms, rounding errors, conditioning problems, and iterative methods. The interaction of condition number and round-off error is at the heart of the matter as far as many of the large problems of modern numerical science are concerned and the authors have achieved a clear and succinct account of this area.

Scientists whose work involves numerical analysis have a need for textbooks at various levels to be available for quick reference. At £3.90 this book is good value and is a worthwhile addition to such collections.

R. DIXON

Radiant heat transfer, by E. M. Feigel'son. 250 mm × 175 mm, pp. iv + 191, *illus.*, (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1974. Price: £8.60.

It is thought that radiative processes may play a part in the origin of anomalies of the general circulation of the atmosphere that continue for a time-scale of months or years. Understanding these effects and their relationship to climatic variation is therefore a fundamental problem of atmospheric physics. Unfortunately many meteorologists find difficulty in understanding the physics of radiative transfer and when faced with introducing their effects into atmospheric models resort to empirical relationships of dubious origin. Professor Feigel'son's book is an attempt to unravel some of the mysteries of radiative transfer in a cloudy atmosphere and examine the validity of some of the approximations that are in vogue. Unfortunately it does not completely succeed. The author's monograph is strictly a text for the specialist. The brief excursions into the realm of general-circulation models and atmospheric dynamics are really a résumé of the state of the art in 1967 when the book was originally written in Russian. There is little discussion of possible improvements to the existing schemes, which indicates that the author has limited experience in this area. A further limitation of the book concerns the neglect of the solar characteristics of cloudy atmospheres. In spite of these deficiencies, the radiative-transfer specialist will find the book an interesting addition to the subject.

An introductory chapter briefly surveys the properties of clouds in terms of their altitude and radiative properties. As usual almost all the discussion is concerned with water-droplet clouds, which emphasizes that we still need detailed information on the radiative properties of ice clouds. The second chapter provides a limited discussion on the instrumentation used to produce the radiative observations discussed in later portions of the book. The main portion of the book is concerned with methods for computing the infra-red energy and surveys the standard methods for clear atmospheres. Techniques for cloudy atmospheres are also considered. The author is critical of the manner in which radiation and clouds are introduced into general circulation models, but provides little in the way of possible improvements.

The final chapters describe numerical experiments which investigate the effects of radiative heat exchange on the development of cloudiness.

The book reflects the scientific interests of the author and does not claim to be a comprehensive description of the subject. The translation of the original Russian text has been carefully edited and the only criticism of the printing concerns the diagrams which are sometimes too small to read all the information they contain. In spite of the limitations stated earlier, the book is a useful addition to the subject which will interest specialists in atmospheric radiative-transfer theory.

G. E. HUNT

Airflow over mountains—research 1958–72, WMO *Technical Note* No. 127, by J. M. Nicholls. 280 mm × 215 mm, pp. xii + 74, *illus.*, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1973. Price: Sw. Fr. 27.

Technical Note No. 34 with the same title covered the years up to 1958. Much has been done since then because of increased flying in the stratosphere. Earlier theories did not have very specific predictions about what took place above the tropopause because there can be so many different kinds of behaviour. With more observations the theories are in a better position to give more understanding.

Mr Nicholls has performed a very valuable task in helping the coming generation of researchers. He was at a disadvantage in having to be fair to everyone, especially since much work is still going on and is developing quite rapidly, particularly to deal with unsteadiness of the flow and three-dimensional aspects. A reviewer can risk being unfair and if this can stimulate interest in the subject through Mr Nicholls's *Technical Note* it will be worth while.

The weather is, as every meteorologist knows, dramatic, and the more we know about it the more dramatic it becomes. One is therefore not impressed by artificial drama of the 'plane (travelling at 200 m.p.h.) is hit by tornado (travelling at 15 m.p.h.)' kind. Thus, on reading 'Suddenly, and without any warning at all, the indicated air speed dropped in under one second from about 198 kt to 150 kt at 47,300 ft . . .', followed by a statement that it 'was literally staggering; I failed to operate the fast recorder or even speak into the tape recorder', one is led to suspect that the intrepid aviator had thought of himself as the driver of a bus load of instruments, so far was he removed from the thinking shop in this research.

The whole object of the exercise was, of course, to find out about unknown phenomena, and research is very inefficient if communication between components is inadequate. At the other end, where high-powered theoreticians set bright young students to work, there is far too much clever mathematics, which gets published all right, but does not get through to the man in the air because it doesn't try to. If it did try, it would concern itself less with more complicated solutions of simple situations and more with simple approaches to complicated situations — which is what exist out there in nature. Many of the mathematical issues that are brilliantly handled arise because of the model chosen, and fade away when the crude realities of three-dimensional unsteady flow intrude. People have gone to quite absurd lengths to obtain more accurate two-dimensional solutions for uniformly stratified airstreams or highly computerized steady two-dimensional solutions in which a rigid lid is placed on the model and several parameters disposed in such a way as to produce something like one of the main features observed in a highly unsteady case over ragged mountains.

But one is never more conscious than in this field of the inability of people to be original. Our thinking jogs along behind our experience, and if that experience is mathematical or hydraulic it comes out in the kind of theory one uses. 'Are you interested in infinite series?' said one well-known author in this field to me during an international conference visit, as we looked up at a magnificent wave cloud, with billows streaming through it: I was embarrassed by my speechlessness.

There is the school that uses 2D vortices, or doublets, or ridges of elliptical cross-section, and obtains the answer far more correctly than ever before, or finds waves from a hemispherical mountain in a uniform stream which would be completely obscured by a host of other waves in a non-uniform one over any shape of mountain. There are those who see hydraulic jumps, with which they feel at home, in streams for which there is not even a pretence of a theory for such phenomena, because they do not understand vorticity in a stratified medium. As for 'critical levels', I feel that a great nonsense has been made out of the blowing up of terms in familiar equations applied out of context. More heresy is needed here. Likewise much has been made of the Richardson number, or rather of efforts to find the imagined universal critical value of it at which shear layers become unstable. This is really quite a trivial problem, for most of the time the Richardson number is either above or below the critical value, and we can never hope in practice to catch it just passing through and about to give rise to instability. What we are concerned with is the mechanisms which cause it to change from a large to a small or negative value, and these abound in waves. I was disappointed to see Mr Nicholls quote a relevant sentence of mine about accelerated airflows out of context because a much more important statement occurred in the previous paragraph of the reference he quotes, viz. 'Therefore, rather unexpectedly perhaps, the most stable layers develop the smallest Richardson number in waves, and so billows are most likely to develop here'. Horizontal acceleration or deceleration of the flow in waves is not a significant destabilizing mechanism, although several authors have fallaciously argued that it is.

It is important that this review should end on a congratulatory note because Mr Nicholls himself has probably done more than most people in recent years to bridge the gap between aviator and theoretician, and any fruit that comes from his efforts will be well deserved. He can be assured that at least one group working on waves is very appreciative.

R. S. SCORER.

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NOTICES

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