Met.O.785
METEOROLOGICAL OFFICE

the meteorological magazine

NOVEMBER 1967 No 1144 Vol 96
Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.785

THE METEOROLOGICAL MAGAZINE

Vol. 96, No. 1144, November 1967

551.582(267.8+53):551.586:612

AN INDEX OF COMFORT FOR BAHRAIN

By G. A. WATT

Introduction.—Previous papers by Stephenson[1] and McLeod[2] examined the climates of Singapore and Gan respectively from the point of view of human comfort, an assessment of which was ascertained by computing effective temperatures from the scale devised by the American Society of Heating and Ventilating Engineers[3] and also published by the Air Ministry.[4] It was decided to conduct a similar investigation for Bahrain in view of the very high humidities which prevail there in the summer. All times quoted in this paper are zone times (zone time = GMT+4 h).

General background.—Bahrain is an archipelago near 26°N 51°E, situated half-way down the Persian Gulf, some 15 to 20 miles from the Saudi Arabian coast and the Qatar Peninsula. About three miles to the north-east of the main island lies Muharraq upon which the airport and the meteorological office are situated.

The Persian Gulf is a relatively shallow expanse of water, having a depth of less than 40 fathoms in the east, but large areas in the west and along the Trucial Oman coast are less than 10 fathoms in depth and generally less than 5 fathoms around Bahrain and the Gulf of Bahrain.

Since several of the points quoted by Stephenson are of particular significance in relation to the Bahrain climate, they are repeated here for easy reference.

(i) It has been suggested that the upper limit of wet-bulb temperature for sustained white labour is 25·5°C.

(ii) The effective temperature can be regarded as an index of comfort which takes into consideration temperature, humidity and wind speed.

(iii) The comfort zone of effective temperature for acclimatized persons in hot regions is between 19° and 24·5°C with an optimum of 20·5°C.

(iv) The critical effective temperature, above which muscular effort would cause the body temperature to rise rapidly to danger level, is probably between 29·5° and 32°C. (As will be seen later, such effective temperatures do occur in Bahrain.)

The climate of Bahrain.—Broadly speaking the climate of Bahrain can be divided into two parts :

(i) winter, November to April

and (ii) summer, May to October.

During the winter months the weather is normally very pleasant with little cloud and maximum day temperatures frequently reach 20° to 25°C. When strong north-westerly winds blow, distinctly chillier conditions can occur, particularly in January and February. Indeed, snow is reputed to have fallen in the early 1940's. On the other hand, a temperature of 38°C has been recorded in mid-March when a south-westerly wind was blowing off the Saudi Arabian desert. These extreme instances, however, are rare. Although most of the island's average annual rainfall of just under 3 inches is recorded in these months, the rainfall is confined to only a few days.

During the six summer months there is little or no cloud and from June to September rainfall is virtually nil. The sunshine is very powerful and sea surface temperatures in the shallower parts of the Gulf gradually rise to between 30° and 35°C. In May and June the humidity is not usually excessive and there is often a fresh wind which reduces any discomfort caused by the heat. In July, August and September winds are usually light and the humidity increases. At this time, wet-bulb temperatures not infrequently reach 30°C, and 33°C has been recorded. Even so the mean relative humidity is lower than during the pleasant winter months and it is clear that the effective temperature would be a much better indicator of comfort.

Summary of data used.—Values of temperature and wind speed were extracted at three-hourly intervals from the daily register for the 5-year period from 1962 to 1966. Means of dry-bulb, wet-bulb and effective temperature and relative humidity were calculated and are shown in Table I and Figure 1. Mean 24-hour scalar wind speeds were found from the three-hourly values, and are plotted in Figure 2.

TABLE I—MEAN DRY-BULB, WET-BULB, EFFECTIVE TEMPERATURE AND RELATIVE HUMIDITY FOR BAHRAIN, 1962–66

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Mean dry-bulb temperature (°C)	17	19	21	25	29	33	34	34	32	29	25	19
Mean wet-bulb temperature (°C)	15	16	18	20	23	26	28	29	27	25	21	16
Mean effective temperature (°C)	9	11	14	18	22	25	27	28	26	23	18	11
Mean relative humidity (per cent)	75	72	67	64	59	57	61	63	66	67	68	73

The range of variation of dry-bulb and wet-bulb temperature and wind speed over each month in Bahrain is such that a good estimate of the true average effective temperature is obtained by using mean temperatures and wind speeds. For example, the true mean effective temperature for August 1965 was 28·6°C, while the mean effective temperature as calculated from mean temperatures and wind speeds was 28·4°C, giving an error of – 0·2 degC. It was found that 91 per cent of all values of effective temperature during August 1965 (using three-hourly observations) lay between 27° and 30°C.

Average values of dry-bulb and wet-bulb temperature and wind speed were calculated at three-hourly intervals and were used to assess the diurnal variation of effective temperature.

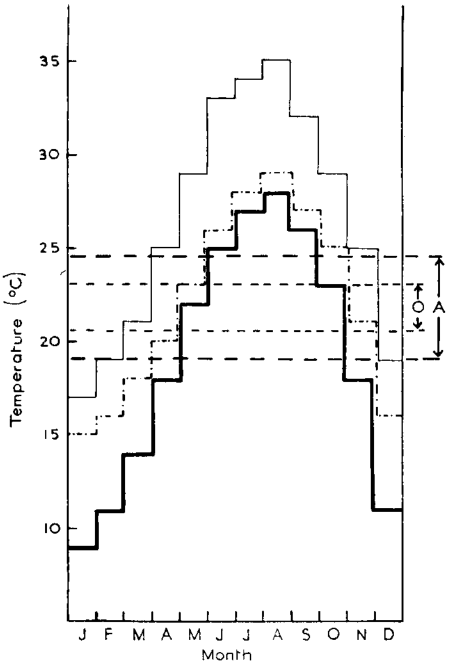


FIGURE 1—MEAN 24-HOUR TEMPERATURES AT BAHRAIN (1962–66)

———	Dry-bulb temperature
·—·—·	Wet-bulb temperature
▬▬▬	Effective temperature
O	Optimum range of effective temperature
A	Acceptable range of effective temperature

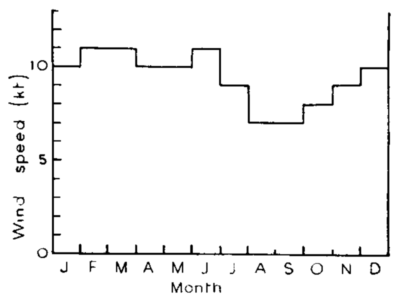


FIGURE 2—MEAN 24-HOUR SCALAR WIND AT BAHRAIN (1962-66)

Discussion of data.—From Table I and Figure 1 it is evident that from November to April the temperatures are not to any degree excessive and the period of acclimatization is short for people new to the region from Europe. The winter period requires no further comment and all subsequent discussion is directed upon the months May to October.

Table I shows that both the mean wet-bulb and effective temperatures have similar values and it would at first appear that wet-bulb temperature is just as good an indicator of comfort as effective temperature. However, from Figure 3 showing the diurnal variations of wet-bulb and effective temperature, it is clear that whereas the wet-bulb temperature remains fairly constant at about 24° to 25°C in May, rising to 28° to 29°C in August, the effective temperature has a minimum around the dawn period and a maximum around 1200–1400 zone time which, as Stephenson also found, seems to occur an hour or so before the time of maximum temperature. This timing

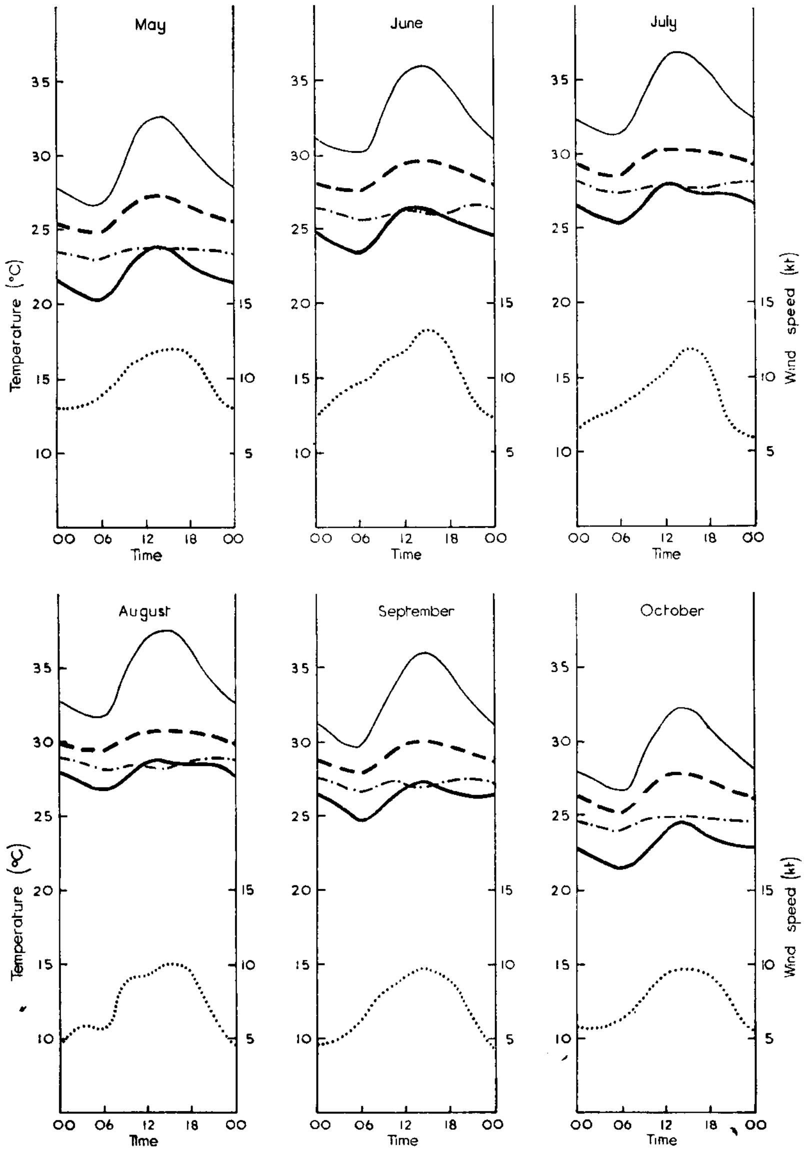


FIGURE 3—DIURNAL VARIATION OF WIND SPEED AND TEMPERATURES AT BAHRAIN

———	Dry-bulb temperature	▬▬▬	Effective temperature
– · – ·	Wet-bulb temperature	– – –	Effective temperature with no wind
. . . . . .	Wind speed		

Times quoted are zone times (GMT+4 h)

is due to the fact that the time of maximum temperature coincides with the time of maximum wind speed, thus tending to reduce the effective temperature slightly. There is also a suggestion of a secondary maximum, or levelling off, of the effective temperature curve especially in July and August around 2000 to 2100 zone time. Even so it is probably still not clear just how much effect the wind has in reducing the effective temperature, and hence increasing human comfort. Values which the effective temperature would assume if calm conditions existed are therefore plotted on Figure 3 and it appears that the effective temperature rises by between 2 degC and 5 degC, assuming the dry-bulb and wet-bulb temperatures remain the same. This assumption proved acceptable from a test sample using occasions of calms and winds of less than 6 kt. It was found that the occurrence of light winds is small during daylight hours but rather more frequent during the night. Nevertheless, places such as non-air-conditioned buildings, tennis courts surrounded by trees and shrubs and open-air cinemas surrounded by high walls will be subjected to winds of considerably reduced speeds compared with those recorded by a properly exposed anemometer. From Figure 3 then, it is clear that for average conditions experienced by a place well exposed to the wind, the effective temperature is always below the acceptable level in May. For calm or light wind conditions, however, the value of effective temperature rises above the acceptable level (24·5°C) for most of the day, but is still well below 29·5°C (the level above which excessive muscular effort could prove dangerous). From July to September, on the other hand, the effective temperature is always above the acceptable level and often exceeds 29·5°C. Even wind speeds of up to 15 kt, whether naturally produced or artificially produced by fans, are insufficient to reduce the effective temperature to

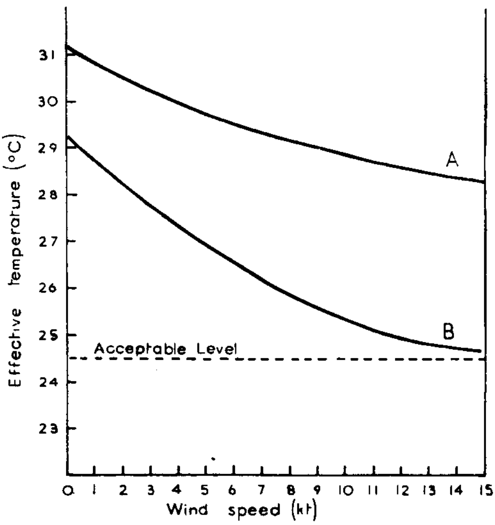


FIGURE 4—VARIATION OF EFFECTIVE TEMPERATURE WITH WIND SPEED AT BAHRAIN AT 0600 AND 1500 ZONE TIME FOR AN AVERAGE AUGUST

A 1500 zone time
Dry-bulb temperature = 37·6°C
Wet-bulb temperature = 28·3°C

B 0600 zone time
Dry-bulb temperature = 31·7°C
Wet-bulb temperature = 28·1°C

below 24·5°C in August, as is evident from Figure 4. However, it was found that on only six occasions during the five years did the effective temperature exceed 32°C — the highest value being 32.9°C. Tables II and III show for each month the number of days on which the effective temperature exceeds 24·5° and 29·5°C respectively at different times of the day. These show that the effective temperature is almost continually above 24·5°C throughout the day between July and September. August has the highest frequency of effective temperatures above 29·5°C.

TABLE II—AVERAGE NUMBER OF DAYS WHEN THE EFFECTIVE TEMPERATURE ⩾ 24·5°C AT STATED TIMES, 1962–66

Zone time	00	03	06	09	12	15	18	21
May	6	4	3	9	14	14	10	7
June	21	17	11	23	28	28	27	25
July	30	28	24	30	31	31	31	31
August	31	31	30	31	31	31	31	31
September	28	25	21	26	30	30	29	27
October	10	8	6	9	15	18	14	10

TABLE III—AVERAGE NUMBER OF DAYS WHEN THE EFFECTIVE TEMPERATURE ⩾ 29·5°C AT STATED TIMES, 1962–66

Zone time	00	03	06	09	12	15	18	21
May	0	0	0	0	0	1	0	0
June	1	0	0	1	1	1	1	1
July	4	3	1	3	5	4	2	4
August	7	6	5	7	11	12	8	8
September	3	1	0	1	2	3	1	1
October	0	0	0	0	0	1	0	0

Comparison with Singapore and Gan.—Table IV compares the mean monthly values of effective temperature at Singapore, Gan and Bahrain.

TABLE IV—MEAN EFFECTIVE TEMPERATURE AT SINGAPORE, GAN AND BAHRAIN

	Period	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Singapore	1952–61	22	23	24	**25**	**25**	24	24	24	24	24	23	23
Gan	1959–64	22	22	**23**	**23**	22	22	22	22	22	21	21	22
Bahrain	1962–66	9	11	14	18	22	25	27	**28**	26	23	18	11

Highest values for each place are bold.

Table IV shows that the least comfortable conditions are experienced during April and May in Singapore, during March and April in Gan and during August in Bahrain. If the figures for these periods are compared, then it is clear that Bahrain has by far the highest effective temperatures, being some 3 degC higher than in Singapore and 5 degC higher than in Gan.

Conclusions.—

(i) Effective temperature is a good index of comfort for Bahrain, as it combines temperature, humidity and wind speed.

(ii) Excessive exercise could prove dangerous at times during the months July to September.

(iii) Forced ventilation by means of fans is inadequate to deal with the conditions during the greater part of the summer.

(iv) The period July to September is the most difficult for acclimatization.

REFERENCES

1. STEPHENSON, P. M.; An index of comfort for Singapore. *Met. Mag, London*, **92**, 1963, p. 338.
2. MCLEOD, C. N.; An index of comfort for Gan. *Met. Mag., London*, **94**, 1965, p. 166.
3. New York, American Society of Heating and Ventilating Engineers. Effective temperature chart showing normal scale of effective temperature. *New York, Am. Soc. Heat. Vent. Engrs. Guide*, 1944, p. 61.
4. London, Air Ministry. Handbook of preventive medicine, A.P. 1269B. London, HMSO, 1959.

551.524.31(411)

THE DIURNAL RANGE OF TEMPERATURE IN SCOTTISH GLENS

By F. H. DIGHT

Introduction.—It has long been suspected that in the glens (valleys) of the 'continental' areas of Scotland, some very large daily temperature variations occur. The observations from four stations considered to be representative of the type of situation envisaged have therefore been analysed.

Data.—The stations and the periods for which data are available, are :

Kincraig (57°08′N 3°56′W, 750 ft) October 1955 – August 1959.
Cannich (57°17′N 4°49′W, 350 ft) 1956–60 (less December 1958, January, February and April 1959).
Halkirk (58°27′N 3°33′W, 232 ft) 1956–60 (less August 1960).
Lairg (57°59′N 4°25′W, 270 ft) August 1956 – December 1960 (less January 1957, July and August 1959).

The periods are short compared with those used in a previous analysis for London stations[1] but in the event, this is no disadvantage and does in fact enhance the interest of the results. There is a reasonable variation in the general character of the different years.

In all cases observations are limited to 0900 GMT daily and all ranges are obtained from the minimum and maximum credited to the day in the returns, i.e. normally the change from the early morning minimum to the afternoon maximum. (Ranging in the reverse direction from maximum to the subsequent minimum was also tried but without significant variation in the results.) Frequency tables are compiled for intervals of 2 degF up to 34 degF and then for 1 degF intervals.

Table I(*a*)–(*d*) gives the mean percentage frequency of daily temperature range within the stated limits, both for months and for the year at the four stations.

Station Locations.—

Kincraig.—A location 6 miles north-east of Kingussie in the Spey Valley which is here orientated south-west – north-east, the relatively flat valley bottom itself being about 1 mile wide, and the valley proper about 3 miles wide.

The station was 500 yd west of the Spey and 50 ft above the lowest ground level; to the south the Spey expands to form Loch Insh which is approximately 1 mile long (south-west – north-east) and ½ mile wide. About ½ mile to the north-west the ground begins to rise fairly steeply out of the valley, the ridge of hills rising to between 1500 and 1800 ft within 1½ miles of the

TABLE I(*a*)—PERCENTAGE FREQUENCIES OF DIURNAL TEMPERATURE RANGES AT KINCRAIG FOR THE PERIOD OCTOBER 1955 TO AUGUST 1959

Range	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
degF						*percentage frequency*							
0–1	–	–	–			0·8	–	–	–	–	–	–	0·1
2–3	4·8	1·8	1·6		–	–	–	2·4	–	1·6	2·5	6·5	1·8
4–5	6·5	5·3	3·2	–	0·8	3·3	3·2	1·6	2·2	4·8	1·7	10·5	3·6
6–7	7·3	8·0	9·7	2·5	0·8	1·7	4·8	5·7	6·7	7·3	9·2	12·9	6·3
8–9	8·9	10·6	7·3	8·3	3·2	1·7	8·1	6·5	8·9	12·1	16·6	8·9	8·4
10–11	9·7	6·2	12·1	10·9	4·8	4·2	11·3	5·6	8·9	17·7	12·5	10·5	9·6
12–13	4·8	8·8	11·3	13·3	10·5	3·3	12·9	14·5	8·9	11·3	5·8	12·9	9·9
14–15	8·1	13·2	12·1	3·3	10·5	15·8	8·1	12·9	13·3	4·8	14·2	7·3	10·2
16–17	12·1	8·0	5·7	10·0	10·5	13·3	6·5	11·3	5·6	8·1	9·2	7·3	9·0
18–19	11·3	5·3	4·0	5·8	8·1	7·5	4·0	10·5	5·6	5·7	6·7	3·2	6·5
20–21	3·2	2·7	4·8	5·8	6·5	6·7	5·7	7·3	5·6	11·3	7·5	5·7	6·1
22–23	6·5	8·0	3·2	8·3	3·2	5·8	7·3	4·8	5·6	4·8	5·8	3·2	5·5
24–25	4·0	5·3	6·5	5·0	6·5	4·2	4·8	4·0	8·9	1·6	3·3	2·4	4·6
26–27	3·2	2·7	4·0	4·2	6·5	8·3	4·0	1·6	3·3	6·5	4·2	3·2	4·3
28–29	4·0	2·7	4·0	7·5	4·8	5·0	5·7	3·2	4·4	2·4	–	4·0	4·0
30–31	4·0	4·4	1·6	3·3	4·0	5·8	2·4	2·4	–	–	0·8	–	2·5
32–33	–	2·7	2·4	1·7	4·8	1·7	4·0	1·6	6·7	–	–	0·8	2·1
34	–	–	0·8	0·8	1·6	1·7	1·6	2·4	2·2			–	0·9
35	–	1·8	1·6	0·8	0·8	0·8	0·8	–	1·1		–	–	0·6
36	0·8	1·8	–	–	0·8	–	0·8	0·8	–		–	–	0·4
37	–	0·9	1·6	0·8	2·4	1·7	1·6		–		–	–	0·8
38	–	–	–	0·8	2·4	–	2·4		1·1		–	–	0·6
39	–	–	0·8	0·8	0·8	2·5	–	–	–	–	–	0·8	0·5
40	–	–	–	1·7	0·8	1·7		0·8	1·1		–	–	0·5
41	–		0·8	4·2	0·8	0·8				–	–	–	0·6
42	–	–		–	1·6	–				–	–	–	0·1
43	–				–	–	–			–	–		–
44					1·6	–				–	–		0·1
45	–				0·8	0·8	–			–	–	–	0·1
46	0·8				–	–				–	–		0·1
47	–		–		–	–				–	–		–
48		–	0·8		–	–				–	–		0·1
49			–		–	–				–	–		–
50				–	–	0·8			–	–	–		0·1

TABLE I(*b*)—PERCENTAGE FREQUENCIES OF DIURNAL TEMPERATURE RANGES AT CANNICH FOR THE PERIOD 1956 TO 1960

Range	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
degF						*percentage frequency*							
0–1	–	0·9	–	–	–	–	–	–		0·6	–	1·0	0·2
2–3	1·6	0·9	0·6	0·8	–	0·7	–	0·6	–	–	–	5·1	0·7
4–5	3·2	6·2	1·9	0·8	0·7	1·3	1·9	1·3	0·7	3·2	1·6	6·2	2·2
6–7	6·5	3·5	3·2	1·6	2·6	2·0	5·1	2·6	0·7	1·9	6·2	6·2	3·4
8–9	10·5	5·3	7·7	3·4	4·5	3·3	5·1	2·6	6·7	9·1	14·7	8·3	6·6
10–11	10·5	5·3	7·8	7·5	4·5	2·6	9·1	12·2	8·0	14·2	12·4	10·3	8·7
12–13	10·5	16·6	9·7	10·0	9·0	8·0	11·7	12·9	8·7	13·6	13·2	15·4	11·4
14–15	10·5	12·2	12·3	9·1	9·7	12·7	8·4	14·7	10·0	9·0	9·4	9·3	10·6
16–17	13·7	15·7	7·7	13·3	9·0	9·3	14·8	7·1	8·7	9·7	8·6	8·3	10·3
18–19	10·5	8·8	8·4	7·5	5·8	9·3	8·4	13·5	11·3	5·8	13·2	11·3	9·4
20–21	6·4	9·7	7·8	8·3	8·4	8·0	7·1	7·7	5·3	6·5	6·2	4·1	7·2
22–23	4·0	2·7	4·5	6·7	9·0	8·7	5·2	7·7	8·0	9·7	4·6	4·1	6·4
24–25	2·4	3·5	6·4	5·0	9·1	6·0	9·7	5·7	4·7	5·8	3·8	7·3	5·8
26–27	2·4	2·6	5·1	10·0	5·8	4·7	5·8	5·8	8·0	3·8	3·1	1·0	5·0
28–29	1·6	0·9	5·2	2·5	6·4	4·7	1·9	3·9	2·7	1·9	0·8	1·0	3·0
30–31	1·6	1·8	2·6	4·2	4·5	4·0	2·6	–	6·7	1·3	–	–	2·5
32–33	1·8	1·8	4·5	4·1	3·8	2·7	1·9	1·3	4·7	0·6	0·8	1·0	2·5
34	0·8	–	1·3	0·8	0·7	2·0		–	0·7	0·6	0·8	–	0·7
35		0·9	1·3	1·7	0·7	2·0	–	–	1·3	0·6	0·8	–	0·8
36		0·9	0·6	2·5	–	2·0	1·3	0·6	3·3			–	1·0
37		–	–	–	2·6	2·0	–	–	–			–	0·4
38	–		–	–	1·3	0·7	–	–				–	0·2
39	0·8		0·6	–	0·6	–	–	–			–	–	0·2
40	–		–	–	–	0·7	–	–		–	–	–	0·1
41	0·8		0·6	–	0·6	0·7	–			0·6	–	–	0·3
42	–		–	–	–	–	–	–		1·3	–	–	0·1
43			–	–		–	–			–	–	–	–
44			–	–		1·3				–	–		0·1
45			–	–	–	–	–			–	–		–
46			–	–	0·7	–	–			–	–		0·1
47		–	–	–		–	–		–	–	–		–
48		–	–		–	0·7			–	–	–		0·1
49		–	–			–	–		–	–	–		–
50		–	–			–	–		–	–	–		–

TABLE I(*c*)—PERCENTAGE FREQUENCIES OF DIURNAL TEMPERATURE RANGES AT LAIRG FOR THE PERIOD 1957 TO 1960

Range	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
degF						*percentage frequency*							
0–1	–	–	–	–	–	–	–	–		0·6	0·7	0·8	0·2
2–3	3·3	2·7	3·2	–	–	–	3·3	1·1	–	1·9	0·7	4·8	1·6
4–5	5·3	2·7	2·4	1·7	2·4	2·5	3·3	5·4	1·3	5·8	1·3	6·4	3·3
6–7	13·9	3·5	8·1	4·2	0·8	4·2	3·3	7·5	5·3	7·7	8·0	13·7	6·8
8–9	12·8	8·9	11·3	7·5	3·2	5·0	6·4	6·4	6·0	11·6	18·7	12·9	9·5
10–11	13·9	8·9	8·9	9·2	3·2	2·5	7·5	7·5	8·7	9·0	15·3	15·3	9·2
12–13	7·5	16·7	13·7	15·0	6·5	4·2	13·9	16·1	14·0	11·0	16·7	9·7	12·2
14–15	15·0	6·2	11·3	10·0	11·3	10·8	13·9	11·8	12·0	14·9	12·7	4·8	11·2
16–17	5·3	13·2	8·1	6·7	11·3	24·2	12·8	7·5	10·7	10·3	3·3	10·5	10·2
18–19	6·4	7·0	5·6	10·8	16·9	12·5	6·4	8·6	6·7	8·4	8·7	10·5	9·1
20–21	5·3	14·1	7·2	5·0	4·8	10·8	9·6	6·4	10·7	7·1	5·3	2·4	7·4
22–23	3·3	5·3	6·4	11·7	6·5	4·2	8·6	6·4	4·7	4·5	5·3	3·2	5·7
24–25	1·2	4·4	8·1	5·8	13·7	5·8	3·3	4·4	6·7	3·2	1·3	1·6	5·0
26–27	2·2	2·7	0·8	3·3	3·2	3·3	2·2	3·3	4·0	1·9	0·7	–	2·2
28–29	1·2	0·9	1·6	3·3	6·5	1·7	3·3	5·4	3·3	1·3	0·7	0·8	2·4
30–31	1·2	1·8	1·6	2·5	3·2	4·2	–	2·2	3·3	–	0·7	1·6	1·9
32–33	–	0·9	0·8	2·5	2·4	1·7	1·1	–	2·0	0·6	–	0·8	1·1
34			0·8	0·8	–	0·8	–			–			0·2
35			–	–	0·8	0·8	–			–	–		0·1
36			–	–	–	–	–		–	–	–		–
37	–	–	–	–	0·8	–	–		0·7	–	–		0·1
38	2·2	–	–			0·8	–		–	–			0·2
39	–	–	–		–		–		–	–			–
40	–	–	–		0·8	–	1·1		–	–			0·1
41		–	–		0·8	–	–		–	–			0·1
42		–	–		–	–			–	–		–	–
43		–	–		0·8	–			–	–			0·1

TABLE I(*d*)—PERCENTAGE FREQUENCIES OF DIURNAL TEMPERATURE RANGES AT HALKIRK FOR THE PERIOD 1956 TO 1960

Range	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
degF						*percentage frequency*							
0–1	0·6	–	0·6		–	–	–	–	–	–	–	–	0·1
2–3	2·6	0·7	3·2	–	1·9	–	0·6	1·6	–	3·2	1·3	2·6	1·5
4–5	5·8	2·8	5·2	1·3	–	2·0	7·7	4·0	2·7	1·9	3·3	5·8	3·6
6–7	11·6	6·3	12·3	4·0	1·3	4·0	8·4	8·9	2·7	7·7	6·0	11·0	7·0
8–9	14·2	4·9	9·7	6·0	6·5	10·0	10·3	11·3	2·7	12·9	10·7	14·2	9·5
10–11	12·3	12·0	11·0	8·0	9·0	5·3	8·4	19·4	7·3	10·3	12·7	10·3	10·4
12–13	16·1	12·0	7·7	15·3	12·3	5·3	12·3	10·5	16·7	9·0	9·3	16·1	11·9
14–15	7·1	14·1	11·0	9·3	7·7	17·3	9·7	10·5	8·7	10·3	14·7	10·3	10·9
16–17	7·1	9·2	5·8	8·7	6·5	16·0	7·7	7·3	13·3	10·3	12·0	7·7	9·3
18–19	7·1	9·2	5·8	13·3	12·3	4·7	10·3	5·6	9·3	14·2	8·0	7·7	9·0
20–21	3·2	12·0	9·7	6·0	11·6	6·0	5·2	9·7	8·0	5·2	6·7	5·8	7·3
22–23	2·6	9·2	6·5	8·0	4·5	10·0	7·1	2·4	9·3	6·5	8·7	3·9	6·6
24–25	3·9	3·5	5·2	6·0	6·5	4·7	4·5	4·0	4·0	1·9	6·0	1·9	4·3
26–27	1·3	2·8	1·3	6·0	5·8	4·7	1·3	0·8	7·3	3·2	–	0·6	3·0
28–29	2·6	0·7	2·6	4·7	5·8	4·7	2·6	1·6	5·3	–	0·7	1·3	2·7
30–31	0·6	0·7	2·6	2·7	2·6	1·9	1·3	0·8	1·3	0·6	–	–	1·3
32–33	–	–		0·7	4·5	1·9	0·6	–	–	1·9		0·6	0·9
34	0·6	–		–	0·6	–	–	0·8	1·3	0·6		–	0·3
35	–	–		–	0·6	0·7	0·6	0·8	–	–		–	0·2
36	0·6	–			–	–	–	–	–			–	0·1
37	–			–	–	0·7	0·6	–	–		–	–	0·1
38	–			–	–	–	0·6	–	–		–	–	0·1
39	–			–	–		–	–			–	–	–
40	–			–				–			–	–	–

site and backed by some peaks of the Monadhliaths within 10 miles. To the south-east the valley accommodates an inflowing tributary of the Spey and the ground rises only slowly until the real ascent to the westernmost ridge of the Cairngorms commences some 2 – 2½ miles away and four peaks reach 4000 ft within 10 miles. The site receives little or no advantage from the westering sun. The situation is indicated in the north-west – south-east sectional diagram, Figure 1 (approximately to scale). The soil is thin and sandy and surface drainage good except for the areas adjacent to the Spey which are very liable to flooding as the valley fall is only about 50 ft in 12 miles. An increasing area in the neighbourhood has been planted with conifers in recent years.

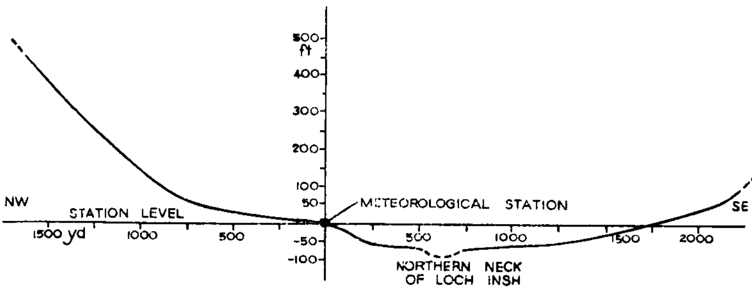


FIGURE 1—TOPOGRAPHICAL SECTION THROUGH THE METEOROLOGICAL STATION AT KINCRAIG

Cannich.—This location differs from that at Kincraig in that it is much more land-locked and has no sizeable water area near. The glen, only about 600 yd wide and again lying south-west – north-east, contains a tributary to the River Glass, the confluence being some two miles to the north-north-east. The forested slopes rise steeply on both sides of the river to the containing hill ridges. The station site is on the south-eastern edge of the flat bottom to this narrow glen, and is cut off from any influence of the westering sun.

Lairg.—The station is sited near a small tributary river running from west-north-west to east-south-east just where the valley opens out for the confluence with the River Shin flowing southwards through the main Achany Glen. The tributary valley has steep sides up to about 800 ft to the south-west, but further upstream to the north-west the ground rises to 1200 ft. The spur to the north is much less high, but the valley side to the main river ultimately rises to some 900 ft to 1000 ft some 3 miles distant to the east. The actual site is on a small ledge approaching 100 ft above the main valley bottom (some 500 yd distant) and some 50 ft above tributary level at its nearest point.

Halkirk.—This site, in a peat bog, is much more open than the other three sites. It is located beside a very small tributary stream to the River Thurso, the confluence being less than 2 miles distant. In the vicinity the ground rises to only 400 ft except for an isolated peak to nearly 800 ft at just over 2 miles. The peat bog in effect forms a rather extensive shallow saucer-like bowl.

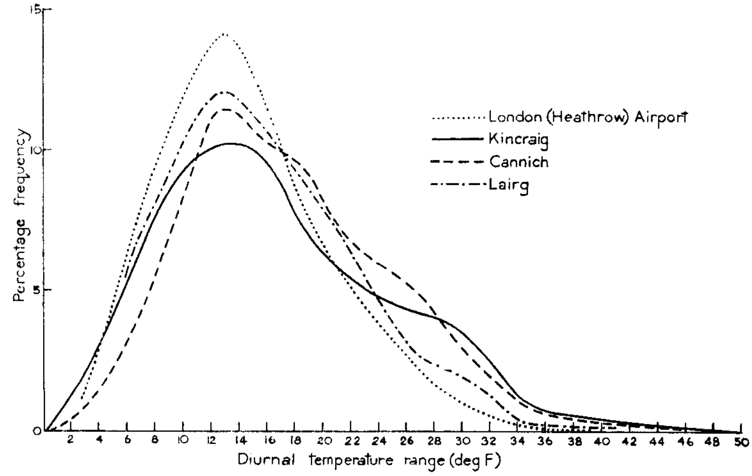


FIGURE 2—COMPARATIVE CURVES FOR ANNUAL PERCENTAGE FERQUENCY OF DIURNAL TEMPERATURE RANGE FOR SCOTTISH GLENS AND LONDON AIRPORT

Extreme temperature ranges: London Airport 37 degF (43 degF once in 10 years), Halkirk 38 degF, Lairg 43 degF, Cannich 48 degF, Kincraig 50 degF.

Comment.—These sites, with the possible exception of Cannich, thus cannot be regarded as typical frost hollows and those at Kincraig and Lairg are both located considerably above the valley bottom.

The average distributions over the year for the three typical glen sites are shown at Figure 2 along with those for London (Heathrow) Airport. The tables and curves for these Scottish stations show some considerable, and in some ways unexpected, differences from the corresponding results for the London area.

Kincraig.—The means for the year show a maximum frequency of 10·2 per cent for the daily range of 14–15 degF as compared with a peak value of 14 per cent at the range 12–13 degF at London Airport. Below these ranges (especially at and below 9 degF) the frequencies for the two widely separated sites are very closely similar. But this similarity disappears as we move into the higher daily ranges; at Kincraig ranges exceeding 21 degF were recorded on nearly 30 per cent of occasions, just twice as frequently as they occurred at the Airport.

These very large ranges are most likely in the period April – July with the extreme range of 50 degF occurring in June. The rather frequent occurrence of these high ranges toward midsummer (normally a dry period in Scotland) at first seems rather remarkable since then the nights are extremely short in these comparatively high latitudes, a factor possibly offset by the lack of evening sunshine at many glen sites. But the high ranges are not entirely the prerogative of the spring and early summer as in southern England and even in the short-period records a range of 36 degF and one of 46 degF have occurred in January (London January maximum range 23 degF), and ranges exceeding 35 degF have been noted in all months except September and October. The highest ranges tend to occur in association with afternoon maxima in the higher 30's or the 40 – 45°F band.

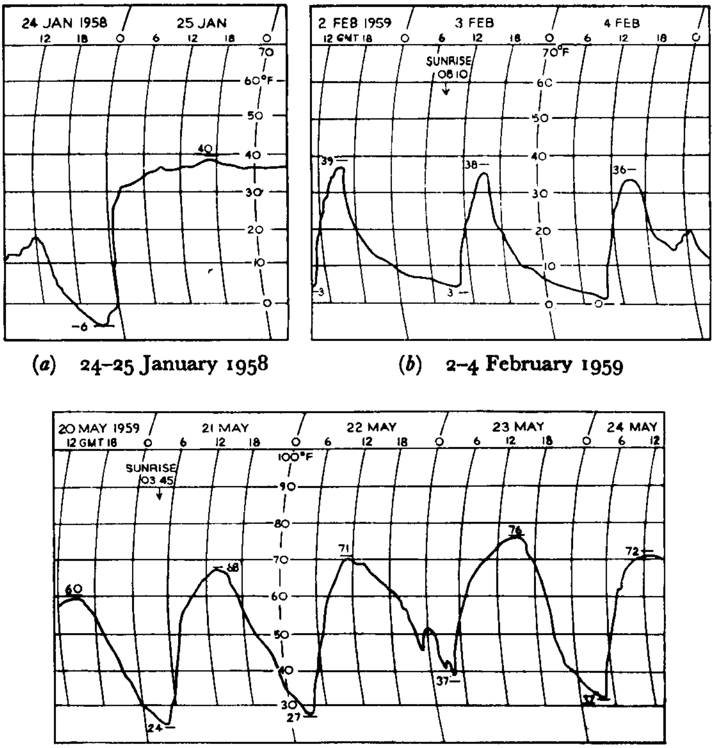
A further point of interest is the two, sometimes three, maxima which show up in most months in the monthly data, suggesting some 'preferred' daily range bands which change slightly with the season. It is difficult to assess how these might be changed in a longer record, except that it seems likely that the consistent maximum approaching a daily range of 30 degF would be emphasized.

It is probably generally appreciated that very low night minima occur in certain parts of Scotland especially in winter and spring and some fairly large diurnal ranges might thus be expected. But this is not the complete story of the not infrequent high to very high ranges recorded throughout the year. It is less widely recognized that 'high' maximum temperatures are prone to occur in these sheltered glens — 'high' that is in relation to the prevailing synoptic conditions of air mass, etc. and in comparison with temperatures recorded in the open lowland belts and the coastal zones in which the major centres of population are located.

Thus 80°F or more was logged (absolute 85°F) on six occasions in the period examined and Williams[2] states that in the three months June–August 1955, maxima of 80°F or above (absolute 87°F) were recorded on 16 days. Specific reference should be made to the day in June 1956 when a morning minimum of 30°F was followed by a temperature of 80°F in the afternoon giving the exceptional range of 50 degF. This accords with Hawke's maximum range values at Rickmansworth.[3] For the short-period Kincraig record, six days per year on average have a diurnal range of 40 degF or more, and practically all of them have occurred in the first six months of the year, and are most likely in May. In the Hertfordshire valley the annual average over the same ranges is five days with June and August preferred. Reproductions of some Kincraig thermograms showing high diurnal range are given in Figure 3 (*a*)–(*c*); unfortunately the thermograph for the outstanding 50 degF range curve probably no longer exists. The very rapid rise of temperature in the forenoon — often more rapid than that at Rickmansworth — should be noted, especially in February when it can hardly be attributed to insolation.

The tables show that large ranges occur with some frequency in the coldest months of the year, and in spite of the very low minima which do occur there is a very pronounced tendency for the maximum temperature to rise above freezing point, however low the minimum. Thus in the four Januarys examined the day maximum has remained as low as 32°F or below on only 20 days. Actually over the whole period the night temperature fell to 3°F or below (absolute −6°F) on 14 nights and only on three of these occasions did frost persist through the day. Snow cover might be expected to mitigate against a sharp rise in temperature during the day, but the interesting fact is that the data do not favour the assumption. In four winters — and those of 1957/58 and 1958/59 had long periods of persistent snow cover — more than half the countryside was under snow on 96 days and on 57 days the 'preferred' daily ranges were from 8 to 19 degF. These were distributed almost equally over the six 2-degree intervals. But 23 days had ranges of from 20 to 33 degF and there was quite a good sprinkling of days with ranges up to 40 degF.

This pronounced tendency for the afternoon temperature to rise above the freezing level in spite of extremely cold nights and thick snow cover is counter to the general experience of the behaviour of even a relatively thin



(*a*) 24–25 January 1958

(*b*) 2–4 February 1959

(*c*) 20–24 May 1959

FIGURE 3—COPIES OF THERMOGRAMS FOR KINCRAIG WITH THERMOMETRIC EXTREMES ADDED

layer of cold air. In the Glasgow (Renfrew) area after a period of frosty weather, the surface 'skin' of frosty air will persist undisturbed for up to 24 hours even after a southerly gradient of near gale speeds has been developed over the area by the general synoptic changes.

What factors operate to produce these rather unexpected features of the climate of the glens? The low night minima liable to occur at all seasons of the year are obviously to be expected from the pooling of the cold air during clear or partly clear radiation nights. It is equally obvious that for most, if not all of the year, the direct insolation possible is far from sufficient to heat the lower layer to the temperatures shown to prevail, especially with the rapidity which is characteristic of the recovery, and a mechanism operating to remove the cold air would seem to be required. In late spring, in summer, and probably in early autumn the rising sun can initiate local convection quite near the surface of eastern facing slopes, a process which continuing, must soon initiate a general movement of the air mass, and so bring warmer air from aloft to the bottom of the glen. But this process can hardly be effective in the colder part of the year particularly with snow cover, even if this is confined only to the higher slopes of the valley. It is suggested that turbulence is generated in the general higher-level airflow by the hills and mountains strong enough to break down the stratification developed in the glen. It is significant that the air temperature in the free air at 1500–2000 ft during the opening days of February 1959 (Figure 3(*a*)) was a degree or two above freezing. Again it is doubtful if an inflow of air from aloft, unless modified, could in many cases effect the considerable temperature rise recorded and to the turbulence would need to be added the heating process of the föhn effect. Williams,[2] remarking on the occurrence of really low temperatures in calm weather, does in fact state 'an increase of wind — often quite sudden — is associated with a rapid rise in temperature, except in the rather rare cases of north-east gales'. He refers to the very low minima on 'calm' nights and one surmises that the 'calm' weather refers solely to the conditions at the valley bottom. It is interesting to note his report in a previous paragraph that 'the highest average run of wind per day was 196 miles' — just over 8 miles per hour.

Cannich.—The curve of annual frequency values follows the same pattern as that for Kincraig, but is displaced markedly to the right for the most part, and is in fact the most displaced of the four curves. The most frequent range is that of 12–13 degF and ranges below this value occur less frequently than in either of the cases studied. Ranges in excess of 17 degF occur more often than at any of the other stations until a range of 36 degF is exceeded when the frequency drops below the corresponding values for Kincraig and the extreme range is 48 against 50 degF at Kincraig.

Lairg and Halkirk.—In both cases the same general tendency is clearly shown, but the curves move quite distinctly toward the pattern for London, Halkirk proving less extreme than Lairg, and both less so than either Cannich or Kincraig. The maximum peak frequency is nearer the peak frequency for London Airport but again the frequencies of the higher ranges are definitely larger than for London, but smaller than for the other two glen locations. Maximum range at Lairg is 43 degF and for Halkirk, 38 degF.

The results in fact illustrate the progressive change in the temperature régime from that of the shut-in glens to more open situations. Thus at Lairg the valley of the small tributary river provides a rather convenient funnel into the main Shin valley for the westerly winds and presumably lessens a possible föhn effect, thereby decreasing the chance of extreme diurnal ranges and 'sharpening' the curve round the 'preferred' range.

At Halkirk, the general configuration is much more open, the backing of high hills/mountains is absent, and the annual curve (not shown) shows a much more pronounced 'sharpening' toward the London pattern.

Acknowledgement.—Acknowledgement is due to Mr H. J. Matthews for considerable assistance with the manipulation of data.

REFERENCES

1. SHELLARD, H. C. and BROWN, P. R.; Frequency distribution of the daily range of temperature at Kew Observatory and London Airport. *Met. Off. clim. Memor., London,* No. 28, 1961.
2. WILLIAMS, C. B.; Studies in the effect of weather conditions on the activity and abundance of insect populations. *Phil. Trans. R. Soc., London,* No. 713, **244,** 1961.
3. HAWKE, E. L.; Thermal characteristics of a Hertfordshire frost-hollow. *Q. Jnl R. met. Soc., London,* **70,** 1944, p. 23.

551·577·33:551·589 (420+429)

SEASONAL RAINFALL SEQUENCES OVER ENGLAND AND WALES

By P. M. STEPHENSON

Introduction.—There has long been widespread popular belief in the compensatory nature of successive winters and summers, e.g. 'a good summer will be followed by a severe winter' or vice-versa. The vast body of weather lore also contains many sayings suggesting relationships of prognostic value between certain months and seasons, e.g. 'a wet June makes a dry September' or 'June wet and warm does the farmer no harm'.[1] However, there have been few attempts to assess the validity of such beliefs objectively, possibly because of the rather formidable nature of the work involved in analysing statistically a sufficiently large quantity of data. One of the more notable analyses of seasonal weather sequences is that by Glasspoole[2] who classified seasonal rainfalls and temperatures following winters of different types using areal rainfall estimates for England and Wales for the 79 years December 1869 to November 1948 and temperatures from 1901. He found little evidence to support any theory that the weather of the following seasons is determined by the weather of the preceding winter, but in spite of this discouraging result and particularly in view of the potential value of any positive results to undertakings concerned with water conservation, it was decided to extend Glasspoole's work for rainfall to cover other seasons using a longer period of data. This decision was reached partly as a result of discussions with the Water Resources Board and partly because of the comparative ease with which the analysis of large bodies of data can now be carried out using the Meteorological Office electronic computer COMET. (Since the present paper was written, Murray[3] has published an analysis of monthly rainfall sequences, carried out on rather different lines from those of Glasspoole and myself, but reaching broadly similar conclusions.)

Data used.—Values of monthly rainfall in inches and tenths for England and Wales are available from 1727 to date and those for the period 1727–1964 have been punched on 5-hole paper tape and more recently transferred to magnetic tape by the Data Processing Branch of the Meteorological Office. The data for 1925 onwards are mainly those prepared for publishing in the annual volumes of *British Rainfall* while the sources of data for the earlier years are described by Nicholas and Glasspoole in an article in the volume of *British Rainfall* for 1931.[4] Broadly speaking the values for the years prior to 1788 are based on the readings of fewer than 10 gauges and on only 2 or 3 gauges up to 1773. From 1821 onwards 20 or more gauges were used and from 1860 more than 50 were employed, while by 1960 this number had grown to over 100 gauges. With the volumes of *British Rainfall* for 1961 onwards (not yet published) a new method[5] of evaluating areal rainfall is being introduced involving the use of over 500 stations and deriving values for areas the size of England by taking means (weighted according to area) of estimates first made for individual River Authority Areas. The magnetic data-tape referred to above uses provisional values for 1962–64 derived from the readings of over 100 stations. Should the values finally published differ markedly from these, the magnetic tape will be amended but it is thought that any discrepancies will be too small to affect the present analysis.

Method of Analysis.—Two computer programmes were written to handle the data on the magnetic tape, the first to deal with six-monthly and the second three-monthly rainfall sequences. Both programmes were designed so that any selected period within the whole 237 years could be analysed.

Running six-monthly and three-monthly rainfall totals were found commencing in each month of the year in turn for each year of the selected period. The totals commencing in any given month were placed in ranking order and the tercile boundaries found, making it possible to form 3×3 contingency tables relating the totals for successive six-monthly or three-monthly periods.

Such tables were prepared, using the computer, for :

(i) six-monthly totals against the following six-months, i.e. January to June against July to December, February to July against August to January and so on. Amongst these are tables which are of interest to the hydrologist e.g. for the winter half-year (October–March) against the summer half-year (April–September) and the summer half-year against the winter half-year.

(ii) three-monthly totals against following three-monthly totals at successive intervals of three months up to a year ahead. These tables include those for the conventional climatological seasons, e.g. spring against summer, spring against autumn, spring against winter and spring against the following spring, where spring is defined as March to May, summer June to August, etc.

In all the tables the terms dry, average and wet are used to describe the three terciles into which the data are classified, these terms being relative to the particular period under analysis in each case.

The periods chosen for analysis were those classified by the Synoptic Climatology Branch of the Meteorological Office as giving rise to predominantly 'blocked' or 'westerly' circulations in the region of the British Isles. They are as follows :

Westerly régime	Blocked régime
1727–1760	1761–1855
1856–1871	1872–1894
1895–1939	1940 onwards

The whole period of 237 years was also analysed, although it was not expected that such a long period, covering as it does climatologically different régimes, would yield results of any particular significance. On the other hand, some of the periods listed above may be thought to be on the short side for reliable statistical analysis, the commonly accepted minimum number of entries in a 3×3 contingency table for statistical testing being 45. However, Craddock[6] has shown that inferences which can be tested statistically may be drawn from a 3×3 table which contains no more than 10 entries and gives a table of significance levels for entries of 10, 15, 20, 25, 30 and 100 showing that these differ little from those of the genuine chi-square distribution. This table was used as a guide in testing the significance of the results obtained in the present work. Moreover, the two later blocked periods (and likewise the two later westerly periods) were grouped together for analysis for those three-monthly sequences from which significant results appeared to be emerging, thus providing more entries for the contingency tables.

Results.—Altogether, 84 six-monthly and 336 three-monthly contingency tables were produced. It is clearly not practicable or desirable to reproduce all of them here so the results will be presented largely in summary form and only the more interesting contingency tables, in particular those relating to the conventional seasons, will be shown.

Six-monthly sequences.

The contingency tables for the whole 237-year period for the summer half-year against the winter half-year and the winter half-year against the summer half-year are shown in Table I.

TABLE I—RAINFALL FOR ENGLAND AND WALES IN TERCILES FOR THE COMBINED PERIOD 1727–1963

(*a*) April–September related to the following October–March

		Oct.–Mar. Dry	Average	Wet	Total
	Dry	28	28	24	80
Apr.– Sept.	Average	28	30	21	79
	Wet	27	19	32	78
	Total	83	77	77	237

(*b*) October–March related to the following April–September

		Apr.–Sept. Dry	Average	Wet	Total
	Dry	27	27	29	83
Oct.– Mar.	Average	24	29	24	77
	Wet	30	22	25	77
	Total	81	78	78	237

Visual inspection of these tables suggests little if any relationship between the rainfall of successive winters and summers and this is confirmed by the chi-square significance test, the values of the chi-square statistic for each table (4·36 and 1·84 respectively) being well below that required for significance even at the 10 per cent level (7·78). In other words, the scores reached in each cell of the tables are not significantly different from those expected by chance. A similar result holds for the 10 remaining tables for this period (January to June against July to December, February to July against August to January, etc.).

Of the 72 contingency tables produced by subdivision of the period into 'westerly' and 'blocked' régimes (6 régimes with 12 tables each) 9 showed significance at the 10 per cent level or better and only 4 at better than the 5 per cent level. The results are summarized in Table II.

TABLE II—SIX-MONTHLY PERIODS PRODUCING SIGNIFICANT CONTINGENCY TABLES DURING WESTERLY AND BLOCKED RÉGIMES

Westerly régimes

Period	First six months	Related six months	chi-square	Significance level *per cent*
1727–60 (34 years)	June–Nov.	Dec.–May	25·27	better than 0·1
	Nov.–Apr.	May–Oct.	7·98	10
1856–71 (16 years)	Mar.–Aug.	Sept.–Feb.	7·95	9
	May.–Oct.	Nov.–Apr.	8·45	7
	July–Dec.	Jan.–June	8·34	7
	Oct.–Mar.	Apr.–Sept.	10·97	2
1895–1939 (45 years)	Aug.–Jan.	Feb.–July	8·00	10
	Sept.–Feb.	Mar.–Aug.	10·40	3

Blocked régimes

Period	First six months	Related six months	chi-square	Significance level *per cent*
1761–1855 (95 years)	Sept.–Feb.	Mar.–Aug.	11·73	2
1872–94 (23 years)	—	—	—	no significant relationships
1940–63 (24 years)	—	—	—	no significant relationships

Although in general these results appear to have little practical application, the following points of interest do emerge :

(i) Such tendency as there is for successive six-monthly periods to be related is confined almost entirely to the westerly régimes and is unlikely to be of prognostic value in the current blocked period (1940 to date).

(ii) Of the four contingency tables having significance at better than the 5 per cent level, three are reproduced in Tables III (*a*)–(*c*) and are for periods coinciding or almost coinciding with the standard winter/summer halves of the hydrological year.

Probably the most one can conclude from these tables is that during westerly régimes a dry winter is more often followed by a dry or average summer than by a wet summer whilst a wet winter is more often followed by a wet or average summer than by a dry summer. Average winters may be followed by either wet or dry but not often by average summers. However, Table III(*d*) shows no relationships and somewhat shatters any confidence one might have in making such pronouncements about other successive six-monthly periods.

(iii) The June to November against December to May table for the period 1727–60 is very highly significant (at better than the 0·1 per cent level) but this may be purely fortuitous, the areal estimates for England and Wales during this period being based on readings of only 2 or 3 gauges.

TABLE III—RAINFALL FOR ENGLAND AND WALES IN TERCILES

(*a*) September–February related to the following March–August 1761–1855 (blocked)

		Mar.–Aug.			
		Dry	Average	Wet	Total
	Dry	8	15	9	32
Sept.–	Average	7	9	15	31
Feb.	Wet	17	7	8	32
	Total	32	31	32	95

(*b*) October–March related to the following April–September 1856–71 (westerly)

		Apr.–Sept.			
		Dry	Average	Wet	Total
	Dry	1	4	0	5
Oct.–	Average	3	2	1	6
Mar.	Wet	1	0	4	5
	Total	5	6	5	16

(*c*) September–February related to the following March–August 1895–1939 (westerly)

		Mar.–Aug.			
		Dry	Average	Wet	Total
	Dry	7	4	4	15
Sept.–	Average	7	2	6	15
Feb.	Wet	1	9	5	15
	Total	15	15	15	45

(*d*) December–May related to the following June–September 1895–1939 (westerly)

		June.–Nov.			
		Dry	Average	Wet	Total
	Dry	5	5	5	15
Dec.–	Average	5	5	5	15
May	Wet	5	5	5	15
	Total	15	15	15	45

Three-monthly sequences.

Of the 16 contingency tables relating the conventional seasons for the 236-year period as a whole, only the one for autumn against winter (Table IV) gives a significantly high value of the chi-square statistic. This table implies that a wet autumn is more likely to be followed by a wet or average winter than by a dry winter but the converse relationship between dry autumns and dry or average winters is not so strongly marked and in fact the high value of chi-square is contributed to in large measure by the comparatively small number, 17, of wet winters following an average autumn.

Hence the westerly and blocked régimes were again considered separately.

(i) *Westerly régimes.*—Of the 144 contingency tables produced for the 3 westerly régimes only 5 were significant at better than the 10 per cent level. These are summarized in Table V, where it will be seen that none of the related pairs of periods occurs more than once and although the table for November to January against May to July (Table VI (*a*)) implies a strong positive correlation between the two periods concerned it may be a freak result due to peculiarities or inadequacies in the 18th century data. Table VI(*b*) suggests a weak negative correlation between successive summers but this is not supported in other westerly periods.

As mentioned earlier (see page 336) a number of tables for a more extended period were prepared by combining tables for the two most recent blocked periods and likewise for the westerly periods. The method used was simply to add together corresponding cells of the relevant individual tables. Although this procedure is not strictly valid since the tercile boundaries are not necessarily identical in different periods it is considered sufficiently accurate to indicate whether or not significant relationships are emerging. In the case of westerly régimes the combined period was one of 61 years (1856–71 and 1895–1939) and only one of the resulting tables for the conventional seasons had a significantly high value of chi-square (Table VII).

TABLE IV—RAINFALL FOR ENGLAND AND WALES IN TERCILES FOR 1727–1963 FOR SEPTEMBER–NOVEMBER RELATED TO THE FOLLOWING DECEMBER–FEBRUARY

		Dec.–Feb. Dry	Average	Wet	Total
	Dry	34	20	29	83
Sept.–	Average	29	28	17	74
Nov.	Wet	20	29	30	79
	Total	83	77	76	236

Chi-square = 9·19, significant at the 6 per cent level

TABLE V—THREE-MONTHLY PERIODS PRODUCING SIGNIFICANT CONTINGENCY TABLES DURING WESTERLY RÉGIMES

Period	First three months	Related three months following	chi-square	Significance level *per cent*
1727–60	Feb.–Apr.	Aug.–Oct.	9·30	5
(34 years)	June–Aug.	Dec.–Feb.	8.11	9
	Nov.–Jan.	May–July	18·05	better than 0·1
1856–71	Dec.–Feb.	Mar.–May	10·88	3
(16 years)				
1895–1939	June–Aug.	June–Aug.	8·10	9
(45 years)				

TABLE VI—RAINFALL FOR ENGLAND AND WALES IN TERCILES FOR WESTERLY PERIODS

(*a*) November–January related to the following May–July 1727–60

		May–July Dry	Average	Wet	Total
	Dry	8	3	0	11
Nov.–	Average	1	7	4	12
Jan.	Wet	2	2	7	11
	Total	11	12	11	34

(*b*) June–August related to the following June–August 1895–1939

		June–Aug. Dry	Average	Wet	Total
	Dry	4	5	7	16
June–	Average	4	6	5	15
Aug.	Wet	9	2	3	14
	Total	17	13	15	45

TABLE VII—RAINFALL FOR ENGLAND AND WALES IN TERCILES FOR WESTERLY PERIODS FOR MARCH–MAY RELATED TO THE FOLLOWING SEPTEMBER–NOVEMBER 1856–71 AND 1895–1939

		Sept.–Nov. Dry	Average	Wet	Total
	Dry	2	8	11	21
Mar.–	Average	10	7	4	21
May	Wet	8	6	5	19
	Total	20	21	20	61

Chi-square = 9·50, significant at the 5 per cent level

This suggests a weak negative correlation between spring and autumn rainfall, although this did not appear in either of the component periods, whilst the relationships which did appear there (last two lines of Table V) are not supported by the tables for the combined period.

(ii) *Blocked régimes.*—Eleven of the 144 tables for the 3 blocked régimes were significant at better than the 10 per cent level and these are summarized in Table VIII.

TABLE VIII—THREE-MONTHLY PERIODS PRODUCING SIGNIFICANT CONTINGENCY TABLES DURING BLOCKED RÉGIMES

Period	First three months	Related three months following	chi-square	Significance level *per cent*
1761–1855 (95 years)	Mar.–May	Mar.–May	9·70	5
	Aug.–Oct.	Aug.–Oct.	12·20	2
	Nov.–Jan.	Nov.–Jan.	8·70	8
1872–1894 (23 years)	Feb.–Apr.	Nov.–Jan.	8·33	9
	July–Sept.	Oct.–Dec.	8·96	7
	Sept.–Nov.	Dec.–Feb.	11·06	3
1940–1962 (23 years)	Feb.–Apr.	Nov.–Jan.	8·53	8
	Mar.–May	June–Aug.	8·05	9
	Sept.–Nov.	Dec.–Feb.	9·10	6
	Dec.–Feb.	Mar.–May	9·22	6
	Dec.–Feb.	Sept.–Nov.	10·71	3

It is of interest that the three examples for the period 1761–1855 relate periods separated by a year although only that for successive springs (Table IX) suggests a meaningful relationship (weak positive correlation), the other two being very unsymmetrical in pattern.

TABLE IX—RAINFALL FOR ENGLAND AND WALES IN TERCILES FOR THE BLOCKED PERIOD 1761–1855 FOR MARCH–MAY RELATED TO THE FOLLOWING MARCH–MAY

		Mar.–May Dry	Average	Wet	Total
	Dry	11	13	8	32
Mar.–	Average	15	4	12	31
May	Wet	7	14	11	32
	Total	33	31	31	95

Of the other relationships listed in Table VIII two are common to both the 23-year blocked periods, namely February to April against November to January and autumn against winter. As might be expected the tables for the combined 46-year period (Table X) support both these relationships and also the one for winter against autumn for 1940–62. However, none of the other relationships shown in Table VIII is repeated in the combined tables nor are any new relationships introduced by them, at least for the conventional seasons.

Of these three combined tables only the first suggests a meaningful relationship, namely a fairly strong positive correlation between the rainfall of the three months February to April and that of the following November to January.

The high values of chi-square given by the other two tables are due almost entirely to an imbalance between only two of the cells in each case and these tables are therefore of limited practical application.

TABLE X—RAINFALL FOR ENGLAND AND WALES IN TERCILES FOR THE BLOCKED PERIODS 1872–94 AND 1940–62

(*a*) February–April related to the following November–January

		Nov.–Jan. Dry	Average	Wet	Total
	Dry	11	5	2	18
Feb.–	Average	3	5	4	12
Apr.	Wet	2	4	10	16
	Total	16	14	16	46

Chi-square = 12·90, significant at the 1 per cent level

(*b*) September–November related to the following December–February

		Dec.–Feb. Dry	Average	Wet	Total
	Dry	9	1	7	17
Sept.–	Average	4	6	3	13
Nov.	Wet	3	7	6	16
	Total	16	14	16	46

Chi-square = 9·20, significant at the 6 per cent level

(*c*) December–February related to the following September–November

		Sept.–Nov. Dry	Average	Wet	Total
	Dry	5	4	7	16
Dec.–	Average	9	3	2	14
Feb.	Wet	3	7	6	16
	Total	17	14	15	46

Chi-square = 8·90, significant at the 7 per cent level

Conclusions.—

Six-monthly sequences.

Such tendency as there is for successive six-monthly periods to be related is confined almost entirely to the westerly régimes, during which there appears to be a weak positive correlation between the rainfall of winter and the following summer. Glasspoole[2] found a similar relationship during the period 1869–1947 for three-monthly seasons, but with a very poor significance level (about 50 per cent).

Three-monthly sequences.

(i) *Westerly régimes.*—No relationship stands out as appearing in all three westerly periods but a combination of the two more recent ones suggests a weak negative correlation between spring and autumn rainfall. Also the comparatively long period 1895–1939 indicates a weak negative correlation between the rainfall of successive summers but this is almost lost when the 16-year period 1856–71 is added.

(ii) *Blocked régimes.*—Again there is no outstanding relationship common to all three blocked periods, although the quite substantial (95 years) period 1761–1855 suggests a weak positive correlation between the rainfall of successive springs. The two later periods are rather short for adequate statistical analysis but taken in conjunction they produce what is in fact the only well-supported relationship of the whole investigation, that is the positive correlation between the rainfall of the periods February to April and November to January. However, this is of limited application and since it stands almost entirely on its own it may be purely fortuitous.

Thus there appears to be little evidence to support much of the weather lore concerning seasonal rainfall or to suggest that this approach to seasonal forecasting of rainfall is likely to prove fruitful.

REFERENCES

1. YARHAM, E. R.; Weather lore of the twelve months. *Weather, London*, **21**, 1966, p. 433.
2. GLASSPOOLE, J.; Seasonal weather sequences over England and Wales. *Met. Mag., London*, **78**, 1949, p. 193.
3. MURRAY, R.; Sequences in monthly rainfall over England and Wales. *Met. Mag., London*, **96**, 1967, p. 129.
4. NICHOLAS, F. J. and GLASSPOOLE, J.; General monthly rainfall over England and Wales, 1727 to 1931. *Brit. Rainf.* 1931, *London*, 1932, p. 299.
5. LEWIS, R. P. W. and GOLDING, B.; Errors in the traditional method of computing general values of monthly and annual rainfall over large areas. *Met. Mag., London*, **94**, 1965, p. 109.
6. CRADDOCK, J. M.; Testing the significance of 3×3 contingency table. *The Statistician, London*, **16**, 1966, p. 87.

REVIEWS

The sea, by R. C. Miller. 11½ in×9 in, pp. 316, *illus.*, Thomas Nelson and Sons Ltd., 36 Park Street, London W1, 1967. Price : £4 4*s*.

The first impression gained on opening the pages of this coffee-table book is one of unrestrained luxury — never has such a wealth of illustration on all aspects of the sea been gathered together into a single volume. The great majority of these breathtaking photographs are new, although a few old favourites crop up occasionally (Gill nets at low tide in the Bay of Fundy, Lightning over Surtsey, etc.). One lacks adjectives to describe the sheer aesthetic appeal of the colour photographs, all of which have been faultlessly printed (by the Chanticleer Press in New York).

Tearing one's eyes away from this visual feast, the reader discovers an enthusiastic text that ranges over the whole field of oceanography, marine biology and navigation. The author, Dr R. C. Miller, is a marine zoologist, so naturally one turns first to the (longest) chapter entitled 'The Life in the Sea'. Scarcely able to do more than skim the surface of this vast subject, the author succeeds in imparting an accurate impression of contemporary attitudes to marine life by concentrating on selected species in the tidal area, coral reefs and the open sea. A page is devoted to the mysterious 'deep scattering layers' whose unknown constituent fishes move up and down regularly with night and day, to the confusion of sonar operators.

Turning to the physical sciences, we find the author on less sure ground. While his aim continues to be a broad impression of, in this case, 'The World of Water', several errors have crept in. Would many physicists agree with the statement that 'Viscosity is what holds water together'? And occasionally an unnecessarily verbose explanation of simple ideas leaves the impression that the author was trying to convince himself as much as the reader. In particular, the page spent defining the difference between weather and climate which ends '. . . summer thunderstorms are a standard feature in any part of the United States east of the Rocky Mountains and are thus part of the climate there. Because they rarely occur on the Pacific coast, they would be regarded as weather.' Unhappy arguments such as these are, however, rare and generally the information offered is reliable if undocumented (the book contains no references).

To sum up, the brilliant photographs make this new book on oceanography a bargain at four guineas, while the popular text provides a lively introduction by a marine biologist.

J. D. WOODS

"*Meteor*" *Forschungsergebnisse ; Reihe A No.* 1 — *Allgemeines : Physik und Chemie des Meeres*, edited by G. Dietrich, W. Hansen and J. Joseph. 11¾ in × 8¼ in, pp. 79, *illus.*, 1966. Price : DM 50. *Reihe B No.* 1 — *Meteorologie und Aeronomie*, edited by K. Brocks and H. U. Roll. 11¾ in × 8¼ in, pp. x+63, *illus.*, 1967. Price : DM 57. Gebrüder Borntraeger, 1 Berlin 38-Nikolassee.

The results obtained by the German research vessel 'Meteor' are being published in a journal type of publication arranged in four series according to the scientific disciplines involved, but published at irregular intervals.

In the series on the physics and chemistry of the ocean (Reihe A) the first number contains a description of the German participation in the International Indian Ocean Expedition, using their research vessel 'Meteor', cruising in the Indian Ocean from November 1964 until April 1965. The Report is well arranged and presented, lists those who participated, lists and describes many of the instruments used (with good illustrations of many of these), and tabulates the numbers of observations made on the ten parts of the cruise. A total of 71 scientists and 21 technicians were involved in obtaining measurements and samples in the fields of physical and chemical oceanography, marine meteorology, geology, geophysics, botany, zoology, planktology, ichthyology, marine microbiology and ship-building. Data are not presented or analysed in this Report, and meteorological observations were kept to a minimum consistent with the needs of research in related sciences.

Also in Reihe A, Number 1, is a paper concerning the structure of hot salty deep water holes examined in the central Red Sea, while the third and last paper deals with 'Transparency measurements in the Persian Gulf and the Gulf of Oman'.

In the series on meteorology and aeronomy (Reihe B) the first number has a varied content, the aim chiefly being to describe and illustrate projects and experiments, not to present or analyse data. In just under 70 pages are reports dealing with :

(i) the meteorological and aeronomical programmes of the 1965 Atlantic Expedition, International Years of the Quiet Sun (IQSY), with the research vessel 'Meteor'. In addition to aerological data, components of the energy-balance were measured in the vicinity of the equator, and measurements made of radioactivity (air, rain and sea), atmospheric electric field-strength, etc. Cloud photographs were taken hourly during day-time. Results of the investigations will be published in this same series.

(ii) results of some radiation balance measurements during the International Indian Ocean Expedition, 1964–65.

(iii) first results of the Ionospheric Observations during the Atlantic Expedition 1965 (IQSY) of the research vessel 'Meteor'.

(iv) optical determination of the continuum-absorption of maritime air-masses in the spectral region of solar radiation.

(v) the daily variation of sea surface temperature in the vicinity of the equator. Measurements were by radiation thermometer.

(vi) instrumentation for wind, temperature and humidity profile measurements at sea, taken during the 1965 Atlantic Expedition by the research vessel 'Meteor' stationed on the equator for several weeks, using an attached buoy which lay 300 m from the ship.

(vii) three-channel radiosonde for continuous recording of temperature, humidity and pressure. More than 100 soundings, using a captive balloon with a ceiling of 2000 m, were recorded by the research vessel 'Meteor' during the 1965 Atlantic Expedition. This paper contains circuit diagrams and photographs.

The editors have arranged that each of the papers has a short summary in English. Many readers will also appreciate the English captions which appear with the tables, figures and photographs. A useful review by F. Model has already appeared in *Deutsche Hydrographische Zeitschrift* Jahrgang 19 Heft 4 1966.

J. COTTIS

The use of ground-based radar in meteorology (excluding upper-wind measurements), WMO Technical Note No. 78, WMO-No. 193. TP. 99. 11 in $\times 8\frac{1}{2}$ in, pp. xvi+104, *illus.*, Secretariat of the World Meteorological Organization, Geneva, 1966. Price : Sw. fr. 14.

'For a full understanding of the potentialities of ground-based radar in meteorology it is necessary to have a clear grasp of what information the radar will supply and what are its limitations. The ability to portray precipitation patterns instantaneously over a large area has undoubtedly led on occasions to extravagant claims of what radar can do. Its inability to live up to these claims leads to sceptisism among the less well informed.' This has been kept well in mind by the writers of this report, and they have succeeded in presenting a fairly balanced picture of the present-day capabilities of weather radar.

This technical paper brings up to date an earlier World Meteorological Organization Technical Note (No. 27) which was published in 1959. It has been prepared by a working group of well-known meteorologists from six countries under the chairmanship of S. G. Bigler (Environmental Science Services Administration). The earlier version had been prepared under the chairmanship of R. F. Jones (Meteorological Office). Essentially it is a down-to-earth handbook, tailored to the needs of the increasing number of meteorologists and hydrologists who now use radar operationally. It is noted that many countries in recent years have installed radars for operational meteorological purposes; indeed a map of the world-wide distribution of weather radars shows that they are in use in as many as 300 locations (although, surprisingly, only one of these is in Britain). Weather radar information now finds application in short-term forecasts, aviation forecasts, hydrology, climatology and in synoptic analysis; however, perhaps its most important application is in severe storm warnings (hurricanes, tornadoes, and hail-storms).

With sometimes quite detailed attention to practical problems, the writers have discussed such matters as :

(i) factors affecting the intensity and portrayal of radar weather echoes,
(ii) types of weather radars and displays,
(iii) recording and transmission of information obtainable from radar displays,
(iv) types of echo from precipitation,
(v) echoes ascribed to phenomena not associated with precipitation,
(vi) practical applications of weather radar information,
(vii) estimates of the rate and amount of precipitation, and
(viii) the photography of radar displays.

Parts 1 to 6 are slight revisions of corresponding parts of the earlier technical note; Parts 7 and 8 are quite new. A brief and rather superficial summary of a discussion on radar measurement of areal rainfall is included as an appendix.

This note is not intended primarily for the research meteorologist and it tends to avoid discussion of techniques that are not yet in common use. For example, there is virtually no discussion of Doppler radar even though it has important potential applications, such as in the measurement of small-scale horizontal and vertical variations in wind velocity and turbulence, and in the detection of tornadoes.

An improvement over the earlier note is the inclusion of references (102 in all), although as the writers point out, these by no means constitute a complete list. There is no index, but the topics are broken down under subheadings which are listed in a table of contents. As before, the figures are inconveniently relegated to an appendix and the entire format is rather unattractive. At 23 shillings (14 Swiss Francs) it is, however, good value for money. It is recommended to any meteorologists likely to be concerned with the practical use of radar regardless of whether or not he has any previous experience in the use of radar. K. A. BROWNING

Light and heat radiation in stratus clouds, by E. M. Feigel'son. 10 in × 7 in, pp. v +245, *illus.*, Oldbourne Press, 1-5 Portpool Lane, London EC1, 1966. Price : £4 1*s*.

The problem of calculating the field of radiation in and at the limits of an optically thick slab of a scattering medium has exercised the skill of many mathematical physicists and mathematicians of the first rank, from Schuster and Schwarzchild through Milne and Eddington to Kourganoff and Chandrasekhar. When non-isotropic scattering elements and selective absorption are involved the governing equations are of extraordinary complexity. A quick glance through Dr Feigel'son's book is enough to convince the prospective reader that she does not shirk this fact. It is a very personal book, in the main a record of the work in this subject of the author herself and other members of the group in the Institute of Atmospheric Physics of the Academy of Sciences of the U.S.S.R. inspired by Professors E. V. Rosenberg and S. Kuznetzov. It does not give a balanced view of the present position of the subject; but this is not hidden. The author has clearly read very widely on the subject — on the mathematical side at least — and though important books and papers have no more than a passing reference in her text the bibliographies at the end of each chapter are an adequate key to wider study.

The groundwork is laid in two long chapters, 'cloudy atmospheres as an optical medium', and 'the scattering of light in clouds'. These open with a summary of the observed properties of stratiform clouds (Stratus in the title should be stratiform : the limitation is dictated by mathematical rather than meteorological considerations). Here, and everywhere where appeal is made to observation, the attitude is rather uncritical; there is little indication of the almost infinite diversity of real clouds. The radiative transfer equation is then developed and the forms appropriate to strong and weak absorption and strong and weak frequency dependence of scattering are set out. There is a section on the optical properties of water droplets, and a brief review of observations and experimental investigations.

The author's method of solution of the transfer equation, which owes much to Chandrasekhar, is then described. I must admit, as a reader with little feeling for mathematics *per se*, to disappointment with this section, and indeed with practically everything else I have tried to read on this subject. It seems reasonable to believe there is a qualitative physical explanation why a thick cloud is predominantly a backward scatterer when it is composed of droplets which individually scatter so strongly in the forward direction; or of why the first of perhaps 30 significant terms in an expansion in Legendre polynomials of the scattering function of a water drop should have such overwhelming importance in certain situations. If this sort of qualitative comment were made it would help me, and I suspect others, on a weary journey through the mathematics. Dr Feigel'son does not provide it, although she comes much nearer to it in a final short section on the inversion problem — the determination of drop-size distributions from observations of transmitted and scattered radiation.

The book is completed by four shorter chapters treating the absorption of solar radiation, the scattering of terrestrial radiation, temperature changes due to solar and terrestrial radiation in and near cloud layers, and the role of radiation in the formation of cloud. The treatment of the first two of these topics is reasonably realistic, and the work on the problem of cloud albedo for terrestrial radiation is particularly original and important. The more general problems are so complex in detail that I feel the author's mathematical treatment becomes little more than an elaborate game — at one point, for example, she says 'we have thus introduced three very serious restrictions which, generally speaking, strongly distort the physical meaning of the problem'. The fourteen conclusions listed on pages 216 and 217 are almost entirely qualitative statements which can readily be established by physical reasoning. I do not suggest that the mathematical investigations should not have been made — qualitative physical arguments can too easily neglect essential detail in a complex situation — but I doubt whether students should be expected to study them, and that is presumably the purpose of a book which in the main elaborates already published research.

The translation appears adequate, though the phrase 'settling inversion' is sufficient to indicate that it is not made by a meteorologist, and a double transliteration produces three different versions of the name Wiener. The Russian term 'scattering indicatrix' is used for the angular distribution of scattering from a single element which Western writers usually term 'scattering function'. If the one or two misprints I noticed are all that exist, typists and proof readers have no cause to be ashamed. Anyone using the book with serious intent will not require a warning to check the nomenclature, definitions and symbolism with care, and will be grateful for the clear way in which these are set out.

G. D. ROBINSON

OBITUARY

Professor Wouter Bleeker

Professor Wouter Bleeker, Director-in-Chief of the Royal Netherlands Meteorological Institute, died suddenly on 17 April 1967, and meteorology lost a unique personality, admired and esteemed all over the world. He held his views strongly, argued his case cogently, and in all his many activities was a man to be reckoned with. But it was impossible to be with him for long without recognizing, behind his seriousness and tenacity of purpose, both warmth and humour. He made good friends in many countries.

Although Bleeker had been head of his service in Holland for only two years, his former chief would be the first to recognize that he had been the active scientific leader of meteorology in his country for more than twenty years. As in many other countries, meteorology in Holland was almost a monopoly of the state Service, and Bleeker's career followed a pattern rather familiar in his generation. With a university training in mathematics and physics, he entered his Institute in 1928 in his twenty-fourth year, and thereafter maintained his scientific interests, including research work of real quality, while performing full-time professional duties, much of the time in aviation weather forecasting. Already before the outbreak of World War II, he was becoming known as the author of important papers, including a much-quoted one in the Royal Meteorological Society's *Quarterly Journal*, 1939, on the wet-bulb and equivalent temperatures.

The war years were difficult in occupied Holland, but at least the curtailment of normal professional work provided an opportunity for pure science, which in Bleeker's case gave us his textbook on synoptic meteorology and a potential for the future which led to notable successes. In 1946 he became Professor in the University of Utrecht, a post which he was able to hold in plurality with his directorship of the Institute. He was visiting Professor in Chicago in 1948–49 and in Florida State University in 1951–52, and on returning to Holland in 1952 became co-ordinator of scientific research in his Institute. His appointment in 1958 as Member of the Royal Netherlands Academy of Sciences was the hall-mark of his standing as a scientist.

During the post-war years Bleeker was also playing an outstanding role in international affairs, especially within WMO, and for the long period of seven years, 1951–58, was President of the Commission for Synoptic Meteorology. His onerous presidential duties, which he performed with distinction and characterisitc thoroughness, naturally made his name familiar all over the world, but his wide knowledge of every branch of his science brought him even wider fame, as editor of the International Cloud Atlas, Chairman of the Advisory Committee for Nuclear Radiation, Chairman of a commission of IUGG on Atmospheric Chemistry and Radioactivity and many other appointments. In all this committee work he was aided by linguistic powers remarkable even for a Dutchman, and certainly in English his precise knowledge could give him the advantage over many a monoglot speaker of English — or American!

Meanwhile, his personal scientific work continued, and for some years, when pure dynamical models of the atmosphere were being developed for numerical weather prediction, Bleeker was the outspoken defender of non-adiabatic thermodynamical processes in large-scale synoptic systems. He was, of course, entirely in the right. He also made special studies of Mediterranean meteorology, and his guidance as Director of a WMO/UNESCO seminar held in Rome in 1958 will be remembered by the many meteorologists from Mediterranean countries who profited by his wisdom on that occasion.

Perhaps the writer of this appreciation may be permitted a personal note. Bleeker was a massive man, two metres in height, and one recalls most vividly a reunion, shortly after the liberation of Holland, with this hungry giant and his family. That was perhaps the best party we ever had together, but there were many others to follow in various countries; Geneva, Rome, Toronto, Helsinki, Paris, Oxford, are among the conference cities which numerous colleagues will associate with Bleeker's stimulating presence. His death, in his sixty-third year, at the zenith of his influence, is a grievous loss to the meteorological community.

R. C. SUTCLIFFE

NOTES AND NEWS

Meteorological Service of the Netherlands

Dr M. W. F. Schregardus has succeeded the late Professor W. Bleeker as Director-in-Chief of the Royal Netherlands Meteorological Institute.

LETTERS TO THE EDITOR

Estimates of extreme precipitation

Some of the problems associated with the estimates of extreme precipitation mentioned by Dr Lockwood[1] stem from vagueness in definition of terms; others arise from a failure to consider probability in space, as well as in time.

The need of the hydraulic engineer for estimates of extreme floods for the design of dams, etc., where failure would be catastrophic, has led to estimates of so-called 'probable maximum precipitation' (PMP) — a term originating in the United States Weather Bureau.

Dr Lockwood writes : 'There are two general methods of estimating PMP; by statistical procedures and by storm maximization techniques'. The statistical procedure to which he refers is that first given in a paper by Hershfield[2] entitled 'Estimating the probable maximum precipitation'. However, a perusal of this paper shows that Hershfield's method is statistical whereas the orthodox method for estimating PMP is primarily deterministic and no return period is normally associated with it.

Hershfield recognizes the basic difference in approach in the United States Weather Bureau Technical Paper No. 40[3] where he states 'Opposed to the probability method of rainfall estimation presented in this paper is the probable maximum precipitation (PMP) method which uses a combination of physical model and several estimated meteorological parameters'.

It is possible of course, to estimate — by one method or another — the probability or return period associated with any given estimate such as a PMP, irrespective of what it is termed. However, it seems desirable to restrict the term PMP to non-statistical methods, rendering the words 'probable maximum' in Figures 2 and 3 of Dr Lockwood's paper redundant.

Dr Lockwood has followed the Glossary of Meteorology[4] and made no distinction between 'maximum possible' and 'probable maximum'. He states in the introduction : 'the highest rainfall meteorologically possible for a given duration over a specific area is called the PMP'. The author has elsewhere[5] traced the history of the change in terminology from the definable term 'maximum possible' to the subjective concept 'probable maximum'.

The problem confronting the designing engineer, is to estimate the probability of a rainfall exceeding a specified amount occurring over the catchment of a storage area. Procedures for determining this probability involve questions of joint probability in space as well as in time which have as yet, been only partly solved.[6,7]

Armadale, Australia G. H. ALEXANDER

REFERENCES

1. LOCKWOOD, J. G.; Probable maximum 24-hour precipitation over Malaya by statistical methods. *Met. Mag., London*, **96**, 1967, p. 11.
2. HERSHFIELD, D. M.; Estimating the probable maximum precipitation. *Jnl Hydraul. Div. Am. Soc. civ. Engrs, New York*, **87**, HY5, p. 99.
3. Washington, United States Weather Bureau. Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years. Technical Paper No. 40, Washington, United States Weather Bureau, 1961.
4. HUSCHKE, R. E.; Glossary of meteorology. Boston, Mass., American Meteorological Society, 1959.
5. ALEXANDER, G. N.; Discussion — Hydrology of spillway design; large structures; adequate data. *Jnl Hydraul. Div. Am. Soc. civ. Engrs, New York*, **91**, HY1, p. 211.
6. ALEXANDER, G. N.; Using the probability of storm transposition for estimating the frequency of rare floods. *Jnl Hydrol., Amsterdam*, **1**, 1963, p. 46.
7. ALEXANDER, G. N.; Application of probability to spillway design flood estimates. Paper for UNESCO conference on 'Flood computations', Leningrad, 1967.

Reply by Dr J. G. Lockwood;

Mr G. N. Alexander has supplied a number of helpful additional references and emphasized the problem of probability in space and in time. One of his main points concerns the term PMP, and I would agree that the word 'probable' in the titles of Figures 2 and 3 should be omitted to avoid confusion with PMP. It seems unreasonable, however, to restrict the term PMP to the value obtained by a particular estimating method which may not be the best method in all circumstances.

If a project has a desired lifetime N, and U is the calculated risk that failure will occur within a lesser interval, then

$$U = 1 - \left(1 - \frac{1}{T_d}\right)^N$$

Where T_d is the design return period for calculated risk U and desired project life N years. If the project life is 100 years and the calculated risk of failure 1 per cent, then the structure must withstand a flood with a return period of about 10^4 years. Clearly it is difficult to estimate by statistical methods, with any confidence, a flood with a 10^4 year return period from say 50 or 100 years of river-flow records. Hence hydrologists have turned to storm maximization methods for estimating extreme floods. Unfortunately, the storm maximization techniques give little indication of the probability of the estimated maximum precipitation occurring. It is never clear if the estimated maximum precipitation has a return period of 10^3 years or 10^{10} years. The statistical methods of estimating extreme precipitation give an accurate probability but an inaccurate precipitation value; the storm maximization techniques give a reasonable precipitation value but little indication of the return-period of the precipitation value. It is for this reason that storm maximization techniques can only be used for so-called PMP estimations.

I would agree that the definition of PMP in the first sentence of my paper is rather vague. It would be better to use the definition suggested in the WMO publication, Guide to Hydrometeorological Practices.[1] 'The term probable maximum precipitation is widely used to refer to the quantity of precipitation that is close to the physical upper limit for a given duration over a particular basin and in a designated length of time.' The Guide also comments that the terms 'maximum possible preciptiation' and 'extreme rainfall' have been used with approximately the same meaning. It is, of course, impossible to estimate the true maximum possible precipitation, only estimates of maximum precipitation with very long return periods can be made. It would appear that the term PMP should be restricted to maximum precipitation estimates with very long return periods, perhaps 10^4 years and longer. The values estimated by Hershfield's method have a return period of about 10^8 years.

I also agree with Mr Alexander[2] in his criticism of the application of PMP concepts to minor river structures and suggest that they should be reserved for major river structures. The techniques available for estimating maximum precipitation values with medium return periods are not particularly good, but until new techniques are developed we must do the best we can with the tools in hand.

REFERENCES

1. Geneva, World Meteorological Organization. Guide to hydrometeorological practices. Geneva, World Meteorological Organization, 1965.
2. ALEXANDER, G. N.; Application of probability to spillway design flood estimates. Paper for UNESCO conference on 'Flood computations', Leningrad, 1967.

Further contribution by Mr F. Singleton

With reference to the letters by Mr Alexander and Dr Lockwood there are a number of points which require clarification.

(i) *PMP*. — The implication of the WMO definition quoted by Dr Lockwood in his letter, and indeed the understanding given to the term by hydrologists and hydrometeorologists in my experience, is that PMP is an estimate of the maximum possible precipitation. It is often the latter that we wish to calculate but methods of derivation are of such imprecision that, in order to avoid the promulgating of extravagant claims, the nomenclature 'probable maximum precipitation' is used. The word 'probable' is unfortunate since it carries statistical overtones which are not intended. Should an engineer design a spillway to cope with the flood calculated from PMP then, assuming that this yields the probable maximum flood (PMF) and that other factors such as snowmelt are not critical for the area under consideration, then the calculated spillway capacity is an estimate of that capacity which may be equalled but never exceeded. Probability of failure would be zero. For this reason, therefore, it is meaningless to attach a return period to PMP or, rather, to PMF.

To avoid the misunderstanding created by the term PMP perhaps it would be advisable to introduce a new term, estimated maximum precipitation (EMP).

(ii) *Derivation of PMP*. — There are several ways in which PMP might be derived. Three such methods used singly or in conjunction are the maximization approach (which seeks to determine that precipitation which would be associated with the most critical concatenation of meteorological events), the storm model approach (which calculates precipitation from hypothetical models, in which the 'microphysical' efficiency with which available vapour is converted into rain is assumed to be unity), and the

Hershfield statistical approach. The last mentioned, although a statistical method, does claim to derive PMP fulfilling the WMO definition. There seems no *a priori* reason why PMP should not be used regardless of approach.

(iii) *Engineers' problems.* — Judging by the enquiries put by Consulting Engineers to the Hydrometeorology Branch at Bracknell the problems confronting the design engineers depend mainly upon the type of dam. For a dam to be constructed of earth and rock our clients wish to know PMF. For masonry dams and calculation of risk whilst a dam is under construction the need is to know the flood for a given return period.

In more general terms, if exceedance of design criteria would lead to loss of life and/or incalculable damage then PMF should be used. If there would be calculable but not excessive loss then the design would be for a design flood of return period not greatly in excess of the data period or, in areas of meteorological homogeneity as defined by Alexander, a return period calculated by spatial and temporal extrapolation of storm experience.

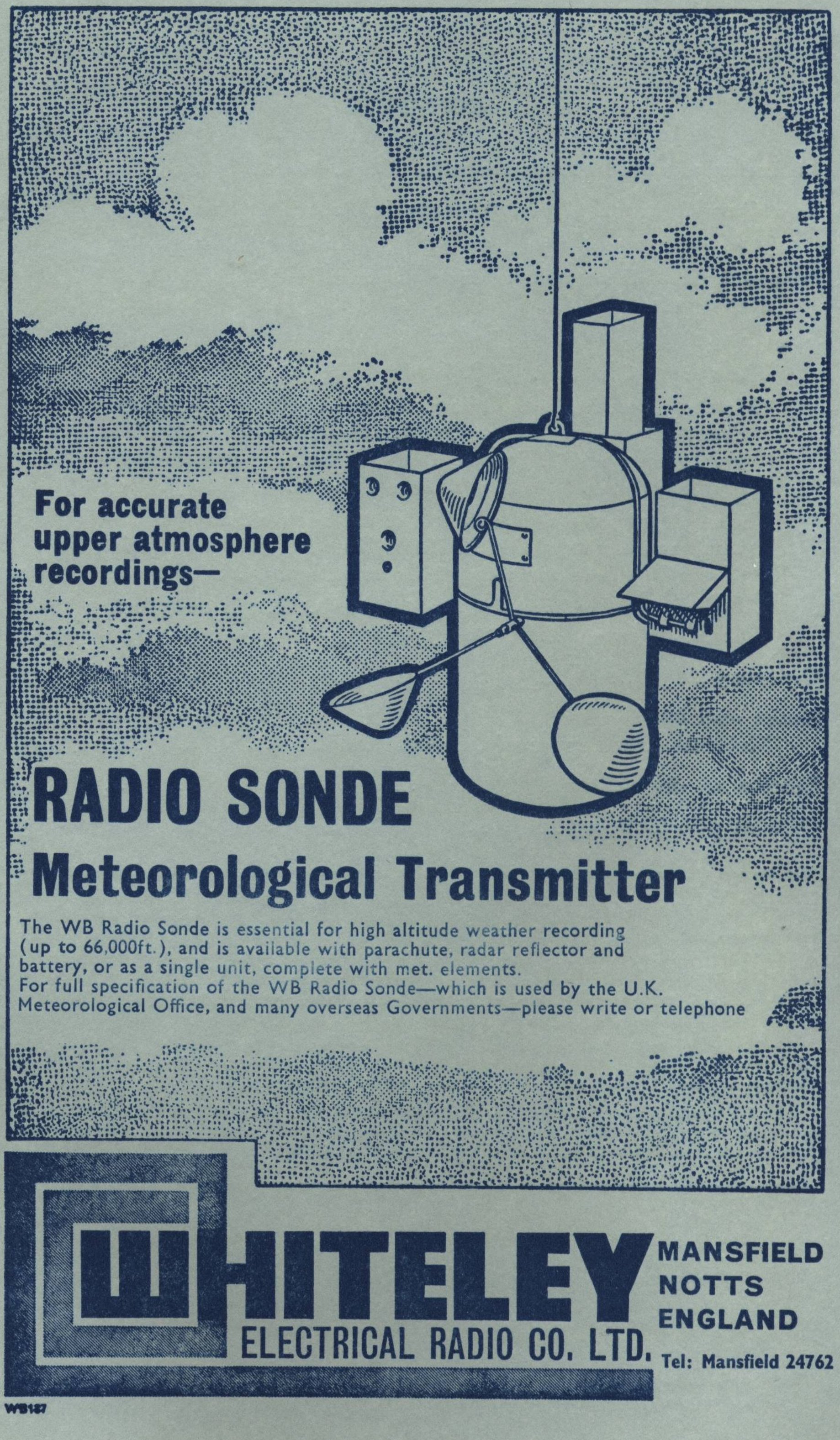
(iv) *Philosophy of PMP.* — Mr Alexander doubts the ability of the meteorologist to calculate PMP. However, it is possible for a given storm type, to estimate upper bounds to the water vapour content of the atmosphere for the storm and the influx of water vapour to the storm. These need not be least upper bounds but could be impossibly high values. With the assumption of unity for the microphysical efficiency an upper bound to the maximum possible precipitation can be calculated. In practice one seeks least upper bounds to the water vapour content and influx estimates and uses efficiencies based on observations of large numbers of storms. The precipitation calculated from these latter values is an estimated least upper bound to the maximum possible precipitation.

OFFICIAL PUBLICATION

SCIENTIFIC PAPER

No. 26 — *A study of vertical air motion and particle size in showers using a Doppler radar*, by P. G. F. Caton, M.A., Ph.D.

A 3·2-cm pulsed Doppler radar has been used to record the vertical velocities of precipitation particles within showers. By making assumptions concerning the minimum terminal velocities of the particles, the pattern of the vertical component of air motion may be derived. The validity of the assumptions and the factors which artificially broaden the spectrum of observed velocities are discussed, and an attempt is made to infer particle sizes and densities corresponding to the implied range of terminal velocities. The analyses of seven Doppler sections are described in detail. The major growth of the precipitation particles has been associated with the regions of upward air motion towards the top of the echo. An abrupt increase in the width of the velocity spectrum just below the 0°C isotherm is a convincing indication of the presence of the ice phase aloft, but if this increase is not observed there remains uncertainty concerning the nature of the particles aloft. In one instance deductions were made from a systematic change in shape of the power–velocity distribution.


For accurate
upper atmosphere
recordings—
RADIO SONDE
Meteorological Transmitter
The WB Radio Sonde is essential for high altitude weather recording (up to 66,000ft.), and is available with parachute, radar reflector and battery, or as a single unit, complete with met. elements.
For full specification of the WB Radio Sonde—which is used by the U.K. Meteorological Office, and many overseas Governments—please write or telephone
WHITELEY
ELECTRICAL RADIO CO. LTD.
MANSFIELD
NOTTS
ENGLAND
Tel: Mansfield 24762
WB187

THE METEOROLOGICAL MAGAZINE
VOL. 96 No. 1144 NOVEMBER 1967

CONTENTS

NOTICE

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire, and marked "for Meteorological Magazine."

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

All inquiries relating to the insertion of advertisements in the Meteorological Magazine should be addressed to the Director of Publications, H.M. Stationery Office, Atlantic House, Holborn Viaduct, London E.C.1. (Telephone: CITy 9876, extn 6098).

The Government accepts no responsibility for any of the statements in the advertisements appearing in this publication, and the inclusion of any particular advertisement is no guarantee that the goods advertised therein have received official approval.

Printed in England by The Bourne Press, Bournemouth, Hants.
and published by
HER MAJESTY'S STATIONERY OFFICE

Three shillings monthly **Annual subscription £2 1s. including postage**
Dd. 133110 K16 11/67 S.O.Code No. 40-43-67-11