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NORTH ATLANTIC SEA TEMPERATURE CLASSIFICATION 1877–1970

By R. A. S. RATCLIFFE

Summary. A classification system has been devised for anomalies of monthly mean sea surface temperature on the North Atlantic. The different types of sea surface temperature anomaly pattern are described and a catalogue, using all available data in the period 1877–1970, is given for most months of that period. Some uses of the catalogue for long-range forecasting purposes are referred to.

Introduction. It has long been clear that the overlying atmosphere affects ocean temperatures, and it has long been suspected by meteorologists that the temperature of the ocean surface may have an appreciable effect on the development of atmospheric systems. It was in studying this latter aspect of air/sea interaction that the need arose to recognize and classify the various patterns of anomaly of sea temperature. The task of getting together the necessary data for classifying almost 100 years of ocean temperature anomalies was a very formidable one and there is still a certain amount of doubt about the pattern in some months.

Data sources. The classification given here is based on four main data sources, viz. :

(i) Sea surface temperature anomalies for 5 degree squares of latitude and longitude produced by Professor Riehl[1] for the region south of 50°N for each month of the period 1888–1936.

(ii) Anomalies produced by the Danish Meteorological Institute[2] for irregular areas north of 50°N for the same or a longer period.

(iii) British and German marine card data for the period 1877–1961 available in the British Meteorological Office.

(iv) Various types of operational data available in the British Meteorological Office for the period 1961–70.

Data sources (iii) and (iv) have been compared with the averages of sea surface temperatures given in an American publication[3] in order to produce the anomalies. Sources (i) and (ii) have their own averages of sea surface temperature but the resulting anomalies in general agree with those produced independently from the data source (iii) so that the entire series is regarded as being as homogeneous as is currently possible. In cases of disagreement in the type of anomaly between the various sources, the month in question has been left unclassified.

The classification. The main classification concerns the sign of the anomaly of sea surface temperature in the area between 35/50°N and 40/60°W, particular importance being given to the sign of the anomaly between 40 and 45°N (see cross-hatching on Figure 1). If there is a well-defined warm

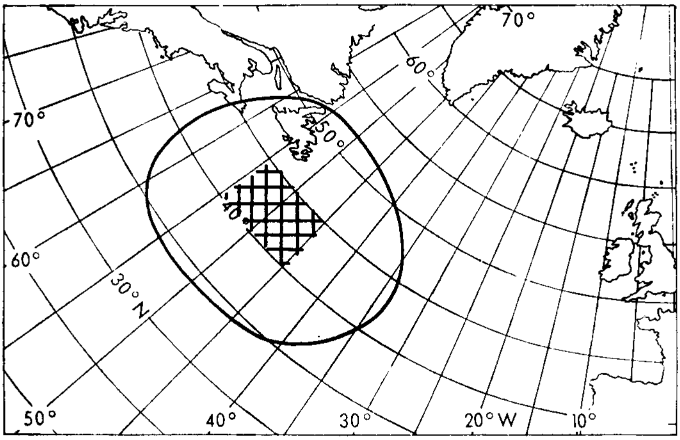


FIGURE 1—AREA OF OCEAN WARMER OR COLDER THAN USUAL FOR MAIN CLASSIFICATION TYPES WP5 (WARM CASE) AND CP5 (COLD CASE)

Displacements east and west of the main anomaly centres by up to 10° are defined as WPE or WPW for the warm cases and CPE or CPW for the cold cases.

or cold pool, anomaly exceeding 1 degC, covering much of this area the classification is WP5 for a warm pool centred near 50°W (Figure 1), WPE for warm pool displaced up to 10° eastwards (i.e. centred between 40 and 50°W), WPW for warm pool displaced up to 10° westwards (i.e. centred between 50 and 60°W) and three similar categories for cold pools, i.e. CP5, CPE and CPW. In the E and W cases particularly the warm and cold pools may extend beyond the eastern or western boundaries respectively of the area as defined. Some overlapping of the classification frequently occurs but this is not important in subsequent research work since similar types lead to similar results. In addition to the 6 main types defined so far, in some months other classifications are possible for a sufficiently large number of years to give a statistically useful sample. These are :

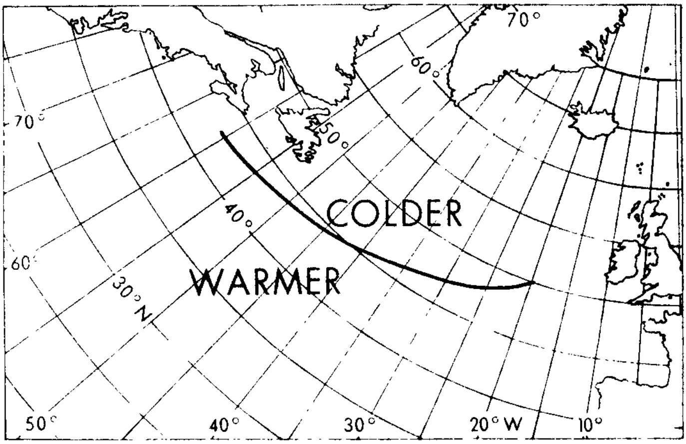
(i) *EZ or enhanced zonality.* In this class the ocean is colder than usual in the north-west Atlantic and warmer than usual in the southern and eastern part of the North Atlantic (Figure 2*(a)*). The line of enhanced sea surface temperature gradient is taken as approximately 40/45°N 60°W to 45°N 40°W to 50°N 20°W.

(ii) *DZ or decreased zonality.* In this case the ocean is warmer than usual in the north-west Atlantic and colder than usual in the southern and eastern part of the Atlantic with the decreased gradient of sea surface temperature approximately along the same line as for EZ (Figure 2*(b)*).

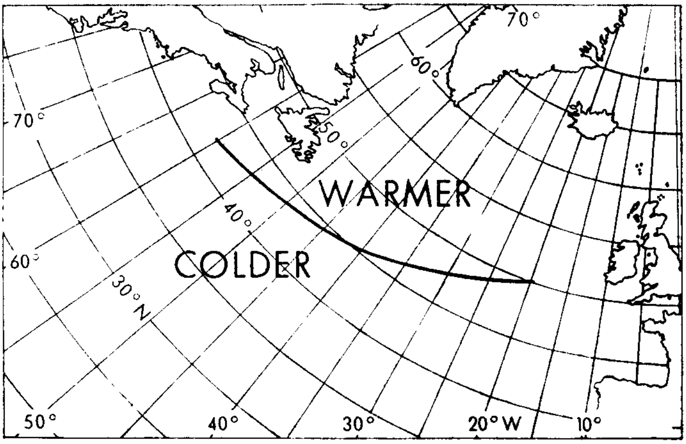
(iii) *MWW or meridional warm west.* When the ocean is warmer than usual in the west (west of about 30°W) and colder than usual east of 30°W including the North Sea and Biscay.

(iv) *MCW or meridional cold west.* When the ocean is colder than usual in the west (west of about 30°W) and warmer than usual east of 30°W including the North Sea and Biscay.

The last two types occur less frequently than any of the others. For some months several classifications are possible, for example DZ often occurs with CP and EZ with WP classification (but rarely vice versa). A blank in the catalogue normally means that the pattern was not sufficiently definite to be classified but occasionally, e.g. during the two world wars and prior to 1888, a blank is due to lack of data.



(a) Enhanced zonality EZ.



(b) Decreased zonality DZ.

FIGURE 2—AREA OF OCEAN WARMER OR COLDER THAN USUAL FOR EZ AND DZ CLASSIFICATION

Uses of the catalogue. The catalogue has been put to a number of uses, for example Ratcliffe and Murray[4] explained how it was possible to use sea surface temperature anomalies as an aid in predicting mean monthly pressure, temperature and rainfall anomalies a month ahead. Their work, which was based on an earlier edition of this catalogue, has since been considerably extended and revised. As a result mean pressure, temperature and rainfall anomalies in months following occurrences of each of the eight main sea temperature anomaly patterns (WP5, WPE, WPW, CP5, CPE, CPW, EZ, DZ) are now available for the British Isles and western Europe together with charts giving some idea of the statistical significance of the results. A further useful by-product of the catalogue has been the deduction of the mean duration of cold and warm patterns in the west Atlantic. If a run of warm or cold months is *not* considered broken by one unclassified month, then the mean duration of cold patterns (CP5, CPE, CPW taken together) is 4·4 months, while the mean duration for warm patterns (WP5, WPE, WPW taken together) is 4·3 months.

The catalogue has also enabled one to deduce the most likely months for the sea temperature anomaly pattern to change. Namias[5] has shown that in the North Pacific, patterns are most persistent during the period December–March and the catalogue results for the North Atlantic are similar.

The most likely period for starting or finishing a run of one particular type of pattern is autumn and spring. A change is most likely at those times on theoretical grounds if one considers that a shallow warm (or cold) layer at the top of the ocean in summer may persist for some months under suitable weather conditions but, once autumn storms begin, the water becomes mixed in greater depth so that an almost isothermal layer becomes established in the top 60 metres or so and when this happens the sign of the anomalies becomes more conservative. Similar arguments can be applied in reverse when the ocean thermocline is established in spring. The chance of a warm or cold pattern which exists in November lasting more or less unchanged over January is approximately 70 per cent while only about 15 per cent change to an opposite pattern; the remaining 15 per cent become indefinite. At the other end of the year approximately 75 per cent of warm or cold patterns existing in May last over July while only about 10 per cent change to the opposite pattern. These facts are important in deducing likely weather for the winter and summer seasons respectively.

February and August patterns (which are important for spring and autumn forecasting) rather surprisingly show at least equal persistence over two months (i.e. to April and October respectively). In each case warm and cold patterns persist on at least 75 per cent of occasions while rather less than 10 per cent change to the opposite type.

In the catalogue in Table I the meaning of the groups is as follows :

CP	CP5	cold anomaly exceeding 1 degC centred near 50°W
	CPE	cold anomaly exceeding 1 degC between 40° and 50°W
	CPW	cold anomaly exceeding 1 degC between 50° and 60°W
WP	WP5	warm anomaly exceeding 1 degC centred near 50°W
	WPE	warm anomaly exceeding 1 degC between 40° and 50°W
	WPW	warm anomaly exceeding 1 degC between 50° and 60°W
DZ	decreased zonality	
EZ	enhanced zonality	
MWW	meridional warm west, ocean warmer than usual west of about 30°W	
MCW	meridional cold west, ocean colder than usual west of about 30°W.	

TABLE I—CATALOGUE OF ANOMALY PATTERNS OF MONTHLY MEAN SEA SURFACE TEMPERATURE IN THE NORTH ATLANTIC 1877–1970

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
1877					CPW								1877
1878					CPW	CPW		CPW		DZ	CPW, DZ	CPW, CP5	1878
1879					WPE, WP5	CPW	CP5, CPE DZ	CPW, CP5	WPE		CP5		1879
1880				CP5	CP5	CPW	CPW		CPW, DZ		CPW, WPE		1880
1881													1881
1882						CPE							1882
1883				WP5			CP5, DZ		CPW, EZ				1883
1884			CP5				CPE						1884
1885													1885
1886			CP5	CPW, CP5	WPE, WP5, EZ	WP5	WP5, WPE	CP5	CPW	CPW			1886
1887		CP5	DZ–WP5	CPW, DZ	WPE		CP5	CP5, MCW	CP5		CP5, WPE		1887
1888	DZ	DZ	DZ, DZ–WP5, CPW–WP5	DZ	DZ, DZ–WPE	CP5, DZ, DZ–WP		CP5, DZ	CP5, DZ	DZ	CPE, CP5, CPW, DZ	CP5, DZ	1888
1889	DZ, CP5	CPW, CP5 DZ	DZ, DZ–WP5	CPE, DZ	WP5	WPW	WP5, WPE	DZ, MWW	WP5, DZ	WPE	WPE, WP5	WPW, WP5	1889
1890	CPW, CP5				EZ		WPE	WP5	WPE		CP5	CP5	1890
1891	CPW, CP5	DZ	CPW–WP5	WPE, DZ, DZ–WP	DZ, DZ–WPE	CP5, DZ, DZ–WP	CP5	CPW		CPE, CP5, EZ	CPE	DZ	1891
1892	WP5, MWW, WPE	WP5	WP5	WPE, DZ, DZ–WP	WPE, CPW, DZ, DZ–WPE	CPW, DZ, CP5	CPW, DZ	WPW, DZ		CPW, DZ	CP5, CPW, DZ	CPW, CP5, DZ	1892
1893	DZ	CPW, CP5, DZ	CP5, DZ, CPW	CPW, CP5, DZ	CP5, CPW, DZ, DZ–WPE	CPW, DZ, CP5	CP5, CPW, DZ	CPW, MCW	CPW, CP5, DZ	CP5, DZ	DZ	CPE	1893
1894	CPE	CPE	CPE			CPE		CPW	CPE, CP5, DZ	CPE	CPE, CP5	CPW, CP5	1894
1895	CPW, DZ, CP5			CPW, CPE, DZ	CPE	CPE	CP5, DZ	CPE, CP5	CPE, CP5, DZ	CPE, CP5	CPE	DZ	1895
1896	CPW, DZ, CP5		CPW, CPW–WP5	CP5	CP5, CPW	CPW	CPW	CPW, EZ		WPW	DZ	CP5, DZ	1896
1897				WP5			CPE	CPE	CPW, CPE, DZ	CP5, CPW, DZ	CPE, CP5, DZ	CP5, CPE	1897
1898	CPW, CP5				WPE		WPE	WPE, WP5		CPE		WP5	1898
1899	DZ	CPW, CP5	DZ, CPW–WP5, DZ–WP5	CPW, WPE	WPE, CPW, DZ, DZ–WPE	DZ	CP5	CPW, MCW	CPW, CP5	CP5, CPW, DZ		DZ	1899
1900		DZ	DZ	DZ	DZ	CPE, DZ, DZ–WP	CPE, DZ	CPE	CPE	EZ	EZ	CPW, EZ	1900
1901						WPW		WPW				WPE	1901
1902	WP5, MWW	WP5, WPE	DZ	DZ	DZ, DZ–WPE	CPW, CP5, DZ, DZ–WP	CPW, DZ	CPE, DZ	CPE, DZ	CPE, DZ	CPE	CPE	1902
1903	CPE	CPE	CPE	CPE	CPE	CP5, CPE	CPE	CPE, DZ	CPE, DZ	CPE, CPW, DZ	CPE, DZ		1903
1904	CPE		CPE	CPE	CPE	CPE	CPE	CPE	CPE		CPW	CPW, CPE	1904

N.B. Groups separated by a 'dash' are hybrids with characteristics of both types.

TABLE I—*continued*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
1905	CPE		CPE, CPW		CPE	CPE	CPE	CPE	CPW	CPW, EZ	CPW	EZ	1905
1906	MWW		WP5					CPE				CPW	1906
1907		EZ	WP5, EZ	EZ				CP5	EZ	CPW, EZ	EZ	EZ	1907
1908			CP5	CPE		EZ, WPW	WPE			CPE	CPE	EZ	1908
1909				CP5	CP5	CP5			WPE	WP5	WPE	WP5, WPE	1909
1910	WP5, MWW	WP5		WP5	WP5						WP5	DZ	1910
1911							DZ	WP5			EZ		1911
1912	CPE	CPE	CPE	CPE	CPE, DZ	CPE	CPE	CPE, DZ				CPE	1912
1913	CPE	CPE	CPE	CPE	CPE, EZ		EZ			WP5, WPW			1913
1914		CPE	CPE		EZ	EZ	EZ	EZ	CPE, CP5, EZ	CPE, CP5, EZ	CPE, CP5		1914
1915	WP5, WPE	WPW	WP5, WPW		EZ		CP5	CP5, MCW	CP5	CPE			1915
1916			EZ, CPW	WP5, EZ	WP5, EZ		WPE					CP5	1916
1917				CPW	CPW, DZ	CPW		CPW					1917
1918													1918
1919		WP5	WP5, CPW–WP5	WP5			WPE	WPE				CPE	1919
1920			EZ	EZ	CPW	EZ	EZ	WP5, EZ		CPE	CPE	CPE	1920
1921			WPW	CPE, EZ	EZ	EZ		CPW, CP5	CP5, EZ	CP5, EZ	CP5	CP5	1921
1922		EZ	EZ	EZ	EZ	WP5, EZ	WP5, EZ	WP5, EZ	WP5	CP5	CP5, CPW, DZ		1922
1923		CP5, EZ	EZ	WP5, EZ	WPE, CPW	EZ		EZ	WPE, EZ	WPE	WPE, WP5	WPW	1923
1924	WP5, MWW, WPE	WP5	WP5, CPW–WP5	WP5	CPW, DZ			WP5, MWW	WPE, WP5	CPW, WPE		CPE	1924
1925	WPW	WP5	WP5, EZ, WPW	WP5, EZ	EZ	WP5, EZ	EZ	WPE, WP5, MWW	WPE	CPW	CP5		1925
1926	DZ, CP5, CPW	CPW, CP5	CP5, CPW	WPW, CPE, CP5	CP5, DZ	CPW	CPE	CPE, MCW	CPW	WP5	WPE, WP5	WP5, WPE	1926
1927	WP5, MWW, WPW	WP5					WP5	WP5, MWW	WPE			WPW	1927
1928		EZ, WPE	EZ	CPW	CPW, DZ		WP5	CPE	WP5				1928
1929	CP5	CP5	CP5, WPW		CPE	CPE, WPW		WPE	WPE, WP5, EZ	WP5, WPW	EZ	EZ	1929
1930		EZ	EZ			WP5, WPW, EZ	WP5	WPE	WP5	WP5	WPW	WPE	1930
1931	WP5, MWW, WPE	WP5, EZ, WPE	WP5	WPE, WP5	WP5	WP5		WPE	WPE, DZ	WPE, WPW		CPE	1931
1932				WPE				WPE, WP5	WPE, WP5	WPE	WPW	WPW, WPE	1932
1933	WPW	WPE	WPW	DZ	WPE, WP5					WP5			1933
1934			EZ	EZ		WPW		WPW	WP5	WP5, WPW	WP5		1934
1935		CP5, EZ	EZ	CPW, CP5, DZ	DZ–WPE	WP5	WP5	WP5	WPE	WPE, WP5, EZ	WP5	WPW, WP5	1935
1936	WPE	DZ, CPW, WPE		CPW, DZ–WP		WP5	WPE	WPE	CPW, WPE			WPW, EZ	1936
1937		WPW			WP5, EZ	WP5	WPE	WPW, WP5	WP5	WPE, EZ		WPW	1937
1938					WP5	WP5, WPW	WP5	WP5	WPE, WP5	WPE			1938
1939			WP5	CP5	CP5, CPW	EZ	CP5	CP5		WP5	CPW, WPE	DZ	1939
1940			CP5	CPW, CP5			WPE						1940
1941			CP5, DZ										1941

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
1942													1942
1943					CPE	CP5		CP5					1943
1944										WPE			1944
1945											CPE		1945
1946		CP5	WPW	CP5		EZ	EZ	WP5	WP5	WPW, DZ	CPE, WPW, DZ	CPE, WPW	1946
1947	DZ, CPE, CP5	CPE, WPW	WPW	CPE	CPE	CPW, CPE	CPE	CPE, WPW	CPE			CPE	1947
1948	DZ	CPW, CP5		CPW, CP5, EZ	WP5, CPE	CPW	CP5		CPW, EZ	CPE	CPE	CPE	1948
1949		WPW	WPW			CPE	CPE	CP5, WPW			WPW, EZ	WPW	1949
1950	WPE	EZ			CP5	EZ	CPE	WP5, EZ	WPE	WPE, WPW, EZ	WPW	WPW, WP5	1950
1951	WP5, WPW	WP5, WPW, WPE	WP5, WPW	WPE, WP5	WPE, WP5	DZ, WPW, DZ–WP	WP5	WPW		WPW, EZ	WP5, WPW	WPW, WP5	1951
1952	WP5, WPW	WP5, WPW	WP5, WPW	WPE, WP5	WPE	WP5	WP5, WPE	WP5, MWW	CP5	WPE, DZ		DZ	1952
1953	DZ, WPW	DZ		DZ, DZ–WP	WP5, DZ, DZ–WPE	EZ	WP5, EZ	EZ	CPE		WPW, EZ	WPW, DZ	1953
1954	DZ, WPW	WP5, WPW	WPW		WP5		WP5, WPE	WPE, MWW	CPW, WPE EZ	EZ	EZ	WPW, WP5, WPE	1954
1955	WP5, WPW	DZ	WP5, DZ–WP5		CP5, CPE, DZ		CP5	EZ, MCW	EZ	EZ		CPW, DZ	1955
1956	DZ	DZ	DZ–WP5			CPW, EZ	CPW	CP5				EZ	1956
1957		CP5	WPW	CPW, CP5	CP5	CP5	CP5		WPE	CP5, CPW		WPW, WP5	1957
1958	WP5	DZ	WP5	WP5, DZ–WP	WP5, DZ, DZ–WPE	DZ, DZ–WP	CPE, DZ	CPE, DZ	CPE, DZ	CP5, CPW, DZ		CPW, DZ	1958
1959	CPW, CP5, DZ	CPW, CP5	CPE	CPW, CP5	CP5, CPW	CP5, CPE	CPE		CPE	CPE, WPW	EZ	WPW	1959
1960				CPE		WP5		WPW, WP5, MWW	WP5	WP5, WPW	WP5	WP5	1960
1961		CPW, CP5, EZ	EZ	CPW	CPW			WPW, EZ	WP5	WPW	WPW	WPE	1961
1962	WPE		CPW–WP5, CPW	CPW, WPE	WPE, CPW	CPE	CP5		CPE			WP5	1962
1963		CPE, WPW	CP5, CPE, DZ, CPW		CP5, CPW	CP5		EZ		WPW, EZ	WPW	WPW	1963
1964	DZ	CPW, CP5, DZ	CPE, DZ, CPW, DZ, WP5		CPE				CPE	WPW	WPW	WPW	1964
1965	CPW, DZ		CPW	DZ, DZ–WP		CPE, DZ				WP5	WP5	WP5	1965
1966	CPE, DZ	CPE, DZ	CPE	DZ, DZ–WP	CPE	DZ, DZ–WP	CPW	DZ		CPE, WP5	WP5, DZ	WP5	1966
1967	WPE	WP5, WPE		WPE, EZ	CPW			WP5, EZ, MWW	WP5, EZ	WPE, WP5	EZ	CPW, WPE	1967
1968	CPW					CP5, CPE	CPE, DZ	CPE, MCW	CPE	CPE, WPW, DZ	CPE, DZ	WPW, WP5, EZ	1968
1969		DZ, WPW	CPW–WP5		CP5	DZ, DZ–WP	CP5, CPW, CPE	CPE			WP5	WP5	1969
1970	WP5	WP5	WP5	DZ, CPW, DZ–WP	CPE		CPE	WPW	WPE		WP5, WPW	WP5	1970

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THE EFFECT OF CLOUD ON SOLAR RADIATION RECEIPT AT THE TROPICAL OCEAN SURFACE

By D. E. PARKER

Summary. Statistical relationships between hourly amounts of total solar radiation and solar elevation at Gan are derived for various states of sky over the island. The investigation begins by making use of cloud observations made from the surface. This treatment is followed by a similiar examination involving cloud data obtained by means of satellites.

Notation.

a	Estimate of the y-axis intercept of a regression line.
b	Estimate of the gradient of a regression line.
C_L, C_M, C_H	The fractional covers of low, medium, and high cloud, according to standard synoptic observations made from the surface.
c_l, c_m, c_h	The actual fractional covers of low, medium, and high cloud.
f	The fraction of solar radiation transmitted by the atmosphere in unspecified conditions.
f'	The fraction of solar radiation transmitted by the atmosphere in cloudless conditions.
N	The fractional cloud cover, according to standard synoptic observations made from the surface.
N_D	Number of data pairs.
Q	The total solar radiation incident on unit area of a horizontal surface at sea level, in the local apparent time (LAT) hour during which the relevant local standard time (LST) cloud observation was made from the surface.
Q_A	The total solar radiation incident on unit area of a surface at the top of the atmosphere and normal to the direction of propagation, during the period of receipt of Q.
r	Correlation coefficient.
s	The mean of the sines of the solar elevation at the beginning and end of the period of receipt of Q.
σ_a, σ_b	Estimates of the standard errors of a, b.

Introduction. This investigation was an extension of work done by Lumb[1] on the influence of cloud on hourly amounts of total solar radiation at the ocean surface in temperate latitudes. Lumb classified the synoptic cloud observations made from the ocean surface and then studied the linear regression of $Q/(Q_A s)$ on s for each category. Because Lumb's classification of cloud types was inappropriate for the tropics, another set of cloud categories for observations from the surface was devised for the present work (Appendix I). This set was so designed that any cloud observation could be fitted into one, but only one, category. The first part of this study consisted of performing linear regression of $Q/(Q_A s)$ on s for each of these categories, comparing the results for the different categories, and making a comparison both with Lumb's results and with figures suggested by Gadd and Keers.[2]

It would be very useful to be able to infer surface radiation from satellite nephanalyses. For this reason the second part of this investigation made use of cloud categories based on satellite observations. These categories (Appendix II) were much broader than those for observations from the surface because of the relatively low resolution of satellite photography. The results of the linear regressions of $Q/(Q_A s)$ on s for these categories were used to make an estimate of the average vertical fractional transmission of solar radiation by the tropical atmosphere.

Data.

(i) *The observing station.* Gan (00° 41′S, 73° 09′E) is an island of area about one square mile on the Addu Atoll in the Indian Ocean. No part of Gan is more than 10 feet (3 m) above sea level, and observations from the island have been assumed to be representative of oceanic conditions.

(ii) *Cloud data.* Cloud observations made from the surface at Gan shortly before the hour (LST), and recorded in the standard synoptic code, were extracted and categorized.

Daily satellite nephanalyses for 1967, covering the tropics between 30°N and 30°S from 15°W via 0°E to 165°E, had previously been prepared by Dent, Parker, and Preedy for research purposes. They were similar to operational nephanalyses but contained rather more detail. Estimates of conditions over Gan were extracted and categorized. The passage of the satellite over Gan was generally about an hour after local noon.

(iii) *Solar radiation.* Solar radiation at Gan was measured by means of a Kipp solarimeter. When the data-logging equipment was working perfectly there were 60 readings of radiation intensity in each hour. Initially, the data used were restricted to hourly totals in 1967 evaluated from at least 50 readings. To obtain reliable regression lines for the less-common surface-observed cloud categories it was necessary to include some 1968 and 1969 data and to relax the requirement from 50 to 30 readings per hour. All the hourly solar radiation totals were for integral LAT hours.

(iv) *Solar elevation.* Solar elevation data for 1967 were supplied with the solar radiation data, in the form of values of s as defined above. Corresponding data for 1968 and 1969 were extracted from astronomical tables.

(v) *The solar constant.* The solar constant was taken to be 135 mW/cm^2.

Results — Part I. The results of the linear regressions of $Q/(Q_A s)$ on s for the 12 cloud categories for observations from the surface are given in Table I. The regressions take the form $Q/(Q_A s) = a + bs$.

The value of $Q/(Q_A s)$ is given by $(a + b)$ when $s = 1$, i.e. when the sun is at the zenith. Hence it is a direct measure of the short-wave radiation transmission of the atmosphere. The values of $(a + b)$ relate in a well-ordered fashion to the cloud categories. The discrepancy in $(a + b)$ for category C was caused by the use of more than two decimal places in the calculations.

TABLE I—RESULTS OF LINEAR REGRESSIONS OF $Q/(Q_A s)$ ON s FOR THE 12 CLOUD CATEGORIES FOR OBSERVATIONS FROM THE SURFACE AT GAN

Cloud category	N_D	a	b	σ_a	σ_b	$(a + b)$	r
A	37	0·57	0·24	0·03	0·05	0·81	0·67
B	21	0·45	0·35	0·05	0·08	0·80	0·73
C	31	0·52	0·22	0·05	0·08	0·73	0·47
D	45	0·49	0·28	0·05	0·06	0·77	0·57
E	33	0·60	0·08	0·04	0·07	0·68	0·22
F	21	0·35	0·35	0·08	0·11	0·70	0·59
G	88	0·46	0·21	0·04	0·06	0·67	0·37
H	80	0·40	0·21	0·04	0·06	0·61	0·37
I	89	0·26	0·19	0·04	0·07	0·45	0·29
J	24	0·38	0·07	0·12	0·17	0·45	0·09
K	37	0·18	−0·03	0·03	0·05	0·15	−0·11
L	12	0·03	0·00	0·02	0·04	0·03	−0·01

When s becomes small, a becomes the dominant term in $(a + bs)$. If a is to be large there must be good transmission when the solar elevation is low. This requires that the absorption should be low and also that only a small proportion of incident solar radiation be reflected. If b is to be large the absorption should be low.

All the results in Table I suffer from statistical scatter. The values of r, the coefficient of correlation between $Q/(Q_A s)$ and s, are included in Table I. These values are significantly different from zero at the 0·1 per cent level for categories *A, B, D* and *G*, and at the 1 per cent level for categories *C, F, H* and *I*; but they are not significantly different from zero even at the 5 per cent level for the remaining categories.

Graphs of the linear regression of $Q/(Q_A s)$ on s for cloud categories *A* and *K* are shown in Figures 1 and 2. The grouping of data with respect to s arose because the observations were at fixed hours and the seasonal change of solar elevation at Gan was slight, especially at times of day when the elevation was low. The scatter in all the results was probably caused by the multiplicity of conditions that could be included in the same cloud category. An additional cause may well have been changes of category during the hour.

The correlation between a and b, as calculated from the 12 pairs of values of a and b in Table I, was 0·52. This value is not quite significantly different from zero at the 5 per cent level. A significant positive correlation would indicate that clouds which only weakly absorb insolation also only weakly reflect it.

The frequencies of occurrence of each cloud category at various times of day in 1967 were calculated (Appendix III). The total frequencies were used to calculate a weighted mean of $(a + b)$ for Gan for 1967. This weighted mean was 0·64, the weighted means of a and b being 0·44 and 0·20 respectively. Note, however, that the frequencies of the cloud categories varied with the time of day, and hence with s. In particular categories *D* and *G*, which refer to strongly convective situations, were more common at 14 LST than at 08 LST.

Some non-linear regressions of $Q/(Q_A s)$ on s were performed for each category but yielded nothing of great value.

Discussion of Part I results. Comparison of the above results with those of Lumb is difficult because the cloud categories used are different from those used by Lumb. Generally, however, the values of $(a + b)$ obtained

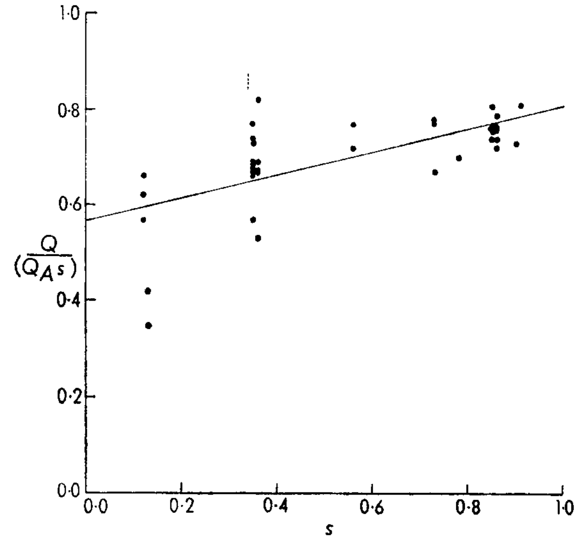

FIGURE 1—LINEAR REGRESSION OF $Q/(Q_A s)$ ON s FOR CLOUD CATEGORY A

The straight line is given by $Q/(Q_A s) = 0{\cdot}57 + 0{\cdot}24s$.

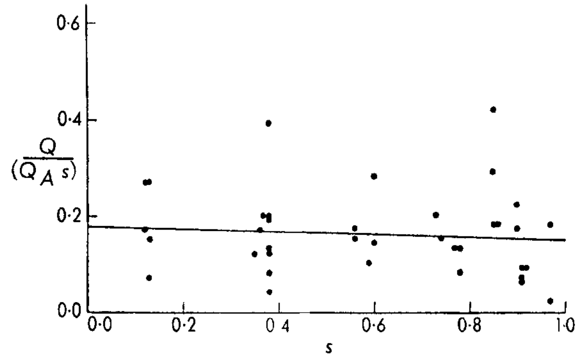

FIGURE 2—LINEAR REGRESSION OF $Q/(Q_A s)$ ON s FOR CLOUD CATEGORY K

The straight line is given by $Q/(Q_A s) = 0{\cdot}18 - 0{\cdot}03s$.

here are similar to those found by Lumb for similar conditions. However there is a tendency for the values of a to be higher and the values of b lower than Lumb's for similar states of sky.

The significance levels of the values of r in Table I are not all that could be desired; nevertheless they are on the whole higher than those obtained by Norris,[3] who repeated Lumb's method using Melbourne data and found the method totally unreliable as a means of predicting hourly insolation totals.

Gadd and Keers proposed an expression

$$f = f' \, (1 - 0{\cdot}4c_h) \, (1 - 0{\cdot}7c_m) \, (1 - 0{\cdot}7c_l),$$

where $f' = 0{\cdot}6 + 0{\cdot}2s$; f is equivalent to $Q/Q_A s$, and the expression predicts $(a + b) = 0{\cdot}8 \, (1 - 0{\cdot}4c_h) \, (1 - 0{\cdot}7c_m) \, (1 - 0{\cdot}7c_l)$. Note that the fractional covers of high, medium, and low cloud are actual ones and not those which would be synoptically reported : they are inferred from humidities in the model discussed by Gadd and Keers. Assuming appropriate values of c_h, c_m, and c_l, values of $(a + b)$ for each cloud category have been predicted from the above expression and compared with the estimated values (Table II). In most cases the predicted values of $(a + b)$ are much lower than the estimated ones. This discrepancy is partly due to the fact that Gadd and Keers chose f' to be equal to the expression for f obtained by Lumb for his category 1, thus assuming that c_h, c_m, and c_l were all zero for this category. If, as assumed for the very similar category A in Table II, $c_h = c_l = 0{\cdot}1$ and $c_m = 0$ for Lumb's category 1, then $f = 0{\cdot}89f'$ for this category, assuming the above expression for f, and Gadd and Keers's value of f' is about 10 per cent too low.

TABLE II—COMPARISON OF ESTIMATED VALUES OF $(a + b)$ WITH PREDICTED VALUES

Values predicted by the expressions :

$$f = (0{\cdot}6 + 0{\cdot}2s)\ (1 - 0{\cdot}4c_h)\ (1 - 0{\cdot}7c_m))\ (1 - 0{\cdot}7c_l)$$

and $$(a + b) = 0{\cdot}9\ (1 - 0{\cdot}2c_h)\ (1 - 0{\cdot}4c_m)\ (1 - 0{\cdot}4c_l)$$

Cloud category	Assumed c_h	c_m	c_l	$(a + b)$ as predicted by 1st expression	$(a + b)$ as predicted by 2nd expression	Estimated $(a + b)$
A	0·1	0·0	0·1	0·71	0·85	0·81
B	0·3	0·1	0·1	0·61	0·77	0·80
C	0·3	0·1	0·4	0·47	0·67	0·73
D	0·3	0·1	0·4	0·47	0·67	0·77
E	0·7	0·1	0·1	0·50	0·71	0·68
F	0·7	0·1	0·4	0·38	0·62	0·70
G	0·7	0·1	0·4	0·38	0·62	0·67
H	0·5	0·4	0·3	0·36	0·60	0·61
I	0·5	0·7	0·3	0·26	0·51	0·45
J	0·5	0·5	0·7	0·22	0·47	0·45
K	0·9	1·0	0·7	0·08	0·31	0·15
L	0·9	0·9	1·0	0·07	0·28	0·03

The values of $(a + b)$ obtained in this investigation are well approximated by the expression $0{\cdot}9\ (1 - 0{\cdot}2c_h)\ (1 - 0{\cdot}4c_m)\ (1 - 0{\cdot}4c_l)$, with the exception of the values of $(a + b)$ for categories K and L for which this expression gives values which are too high. This may be because a complete cloud cover over Gan is usually associated with intense systems giving very thick cloud and consequently severe depletion of solar radiation; categories K and L indicate over 80 per cent and over 95 per cent respectively for insolation depletion by the cloud cover, although with statistical scatter. Although category K permits broken low cloud below the medium-cloud overcast, these values contrast with figures of 50 to 60 per cent for medium-cloud overcasts and 65 to over 80 per cent for low-cloud overcasts given by Haurwitz[4] who used data for Blue Hill near Boston, Massachusetts, U.S.A.

Allowing for the possible presence of higher cloud above the overcasts, Haurwitz's figures would together indicate coefficients of about 0·5 for c_m and about 0·6 for c_l in the latter expression. The coefficient of 0·2 for c_h, however, agrees with Haurwitz's estimate of 20 per cent depletion of insolation by high-cloud overcasts. Haurwitz's investigation referred to here was restricted to cases where there was a complete overcast of a given cloud type.

The results of Mooley and Raghavan[5] who studied insolation at Madras under various overcasts, mainly of high cloud, would indicate a coefficient nearer 0·3 for c_h. However, Raman[6] in his study of data for Poona, found depletion of insolation by thick cirrostratus overcasts to be about 20 per cent and by thin ones about 10 per cent. Raman also gave figures of 30 to 60 per cent for medium-cloud overcasts and 75 to 85 per cent for thick overcasts of very low cloud.

The values of $(a + b)$ predicted by the expression $(a + b) = 0{\cdot}9\ (1 - 0{\cdot}2c_h)\ (1 - 0{\cdot}4c_m)\ (1 - 0{\cdot}4c_l)$ are included in Table II.

Results — Part II. The results of the linear regressions of $Q/(Q_A s)$ on s for the four cloud categories based on satellite observations are shown in Table III, which is analogous to Table I. The cloud category for a given day was regarded as valid for all hourly measurements of Q during that day.

TABLE III—RESULTS OF LINEAR REGRESSIONS OF $Q/(Q_A s)$ ON s FOR THE FOUR CLOUD CATEGORIES FOR OBSERVATIONS FROM SATELLITES

Cloud category	N_D	a	b	σ_a	σ_b	$(a + b)$	r
1	81	0·33	0·37	0·05	0·07	0·71	0·53
2	79	0·52	0·17	0·04	0·06	0·69	0·31
3	56	0·35	0·18	0·06	0·10	0·53	0·24
4	86	0·23	0·06	0·06	0·08	0·29	0·09

The results in Table III all show considerable scatter. The values of r for categories 1 and 2 are significantly different from zero at the 0·1 per cent level and the 1 per cent level respectively; but those for categories 3 and 4 are not significantly different from zero even at the 5 per cent level. A graph of the linear regression of $Q/(Q_A s)$ on s for category 1 is shown in Figure 3. The scatter in all these results was probably caused both by the multiplicity of conditions that could be included in one cloud category and by changes of category during the course of a day. The four sets of results were based on 11, 10, 7 and 12 days' satellite data respectively.

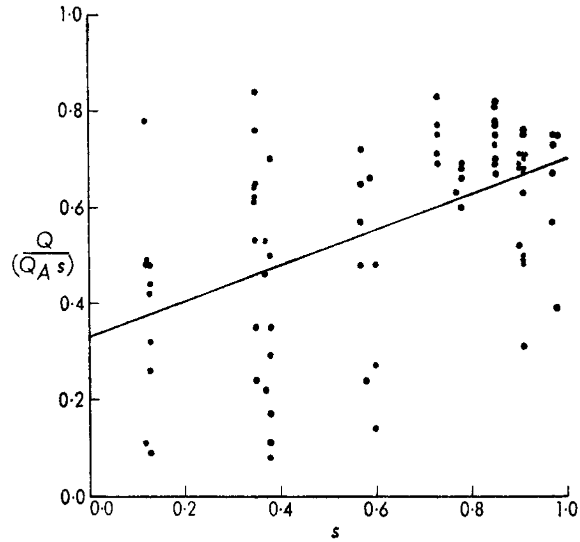

FIGURE 3—LINEAR REGRESSION OF $Q/(Q_A s)$ ON s FOR CLOUD CATEGORY 1

The straight line is given by $Q/(Q_A s) = 0{\cdot}33 + 0{\cdot}37s$.

In the cases of categories 1, 3, and 4, Gan was usually near a category boundary. This probably made the estimate of $(a + b)$ too low for category 1 and too high for categories 3 and 4.

The four categories were allotted to Gan for 118, 131, 43, and 73 days of 1967 respectively, resulting in weighted means for Gan of 0·60 for $(a + b)$, 0·38 for a and 0·22 for b.

Each one-degree square in the area 30°N to 30°S, 15°W via 0°E to 165°E was assigned one of the four categories for each day of 1967. The mean proportions of the total number of squares allotted to the respective categories were 42·5, 22·8, 18·5, and 16·2 per cent. Applying the values of $(a + b)$ in Table III and neglecting variations of square size with latitude resulted in estimates of weighted means for the whole area of 0·60 for $(a + b)$, 0·36 for a and 0·24 for b.

The weighted mean values of a and b for Gan obtained by means of satellite cloud data (0·38 and 0·22) are very similar to those obtained by means of standard synoptic cloud data (0·44 and 0·20). This established the general reliability and usefulness of the satellite method.

The weighted means from satellite data of a and b for Gan and for the large area of the tropics are also very similar. This is in spite of a distribution of categories at Gan considerably different from the mean distribution: the differences cancel out.

The weighted mean from satellite data of $(a + b)$ for the large area of the tropics indicates that the tropical atmosphere transmits about 60 per cent of vertically incident solar radiation. When it is considered that the transmission will be less than this for solar radiation not vertically incident, this figure can be seen to indicate a lower level of insolation in the tropics than the 64 per cent implied by Vonder Haar and Hanson.[7] However, the figures given by these authors were for the zone 0°N to 20°N around the globe, whereas the figure given here refers to the zone 30°N to 30°S around only half the globe.

Conclusions. It is evidently impossible to predict individual hourly radiation totals at a given point at the tropical ocean surface either from synoptic cloud observations made from the surface, or from satellite cloud photographs, at least without narrowing the cloud categories considerably from their width in this investigation. The scatter was considerable in all the results obtained.

However, given sufficient data it would be possible to estimate a and b for each cloud category more precisely than has been done here; as a result, the mean radiative conditions for a given cloud category and a given value of s would be more accurately known. In particular, it would be possible to determine with considerable precision the total solar radiation receipt at the tropical ocean surface over a large area in a given hour by means of the satellite photographs. The uncertainty in the present work of the estimates of a and b is highlighted by the values of σ_a and σ_b in Tables I and III.

Increased precision in the estimation of the spatial weighted means of a and b by means of satellite photographs would be of value to albedo determinations. Latitudinal variations of a and b for a given category would have to be taken into account in such a project. This would require the relation of radiation measurements at the ocean surface to satellite observations at perhaps 10-degree latitude intervals, and similar work for continental and high-altitude surface radiation measurements.

If the relationships in all latitudes of *a* and *b* to cloud amounts at specific levels were investigated further, improved results might be obtained from empirical radiation schemes in general circulation models. Such an investigation might also improve the representation in these models of the role of the tropics in the general circulation of the atmosphere.

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Appendix I

Cloud categories for observations from the surface.

Category	Synoptic code description	Visual description
A	$C_L \leqslant 1$ okta. $N \leqslant 2$ oktas	Clear or virtually clear sky
B	$C_L \leqslant 1$ okta. $N \geqslant 3$ oktas Either $C_M \leqslant 2$ oktas or no C_M in 8-group Either $C_H \leqslant 3$ oktas or no C_H in 8-group	Little or no low cloud but small to medium amounts either of medium cloud or of high cloud or of both.
C	$C_L = 2$ to 4 oktas C_L not of type 2, 3, or 9 No C_M in 8-group Either $C_H = 3$ oktas or no C_H in 8-group	Small to medium amounts of low cloud with little vertical development. Either no medium or high cloud, or small to medium amounts either of medium cloud or of high cloud or of both.
D	$C_L = 2$ to 4 oktas C_L of type 2, 3, or 9 No C_M in 8-group Either $C_H = 3$ oktas or no C_H in 8-group	Small to medium amounts of low cloud with moderate or strong vertical development. Medium and high clouds as in *C*.
E	$C_L \leqslant 1$ okta Either $C_M \leqslant 2$ oktas or no C_M in 8-group $C_H \geqslant 4$ oktas	Little or no low cloud. Either no medium cloud or small to medium amounts of medium cloud. Sky at least half covered with high cloud.

F	$C_L = 2$ to 4 oktas C_L not of type 2, 3 or 9 No C_M in 8-group $C_H \geqslant 4$ oktas	Small to medium amounts of low cloud with little vertical development. Medium and high clouds as in *E*.
G	$C_L = 2$ to 4 oktas C_L of type 2, 3 or 9 No C_M in 8-group $C_H \geqslant 4$ oktas	Small to medium amounts of low cloud with moderate or strong vertical development. Medium and high clouds a sin *E*.
H	$C_L = 0$ to 4 oktas $C_M = 3$ or 4 oktas	Sky up to half covered with low cloud and half or nearly half covered with medium cloud.
I	$C_L = 0$ to 4 oktas $C_M = 5$ to 7 oktas	Sky up to half covered with low cloud and largely covered with medium cloud.
J	$C_L = 5$ to 7 oktas $C_M \neq 8$ oktas	Sky mostly covered with low cloud, without a complete overcast of medium cloud.
K	$C_M = 8$ oktas	Complete overcast of medium cloud not completely obscured by low cloud.
L	$C_L = 8$ oktas	Sky completely covered with low cloud.

Appendix II

Cloud categories for observations from satellites.

Category	Estimated fractional cloud cover *per cent*
1	< 20
2	20 to 50
3	50 to 80
4	> 80

Appendix III

Frequencies of the cloud categories for observations from the surface for Gan during 1967.

Cloud category	08 LST	11 LST	14 LST	17 LST	Total
A	40	42	32	35	149
B	15	15	15	22	67
C	10	10	8	9	37
D	48	65	82	52	247
E	59	52	36	43	190
F	6	3	3	3	15
G	57	66	76	78	277
H	39	36	44	46	165
I	55	43	34	47	179
J	15	16	12	11	54
K	16	13	21	18	68
L	5	4	2	1	12

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ON THE PERFORMANCE OF VARIOUS TYPES OF RAIN-GAUGE IN THE FIELD

By L. S. CLARKSON

Summary. An array of rain-gauges of various types was set up at Easthampstead to include standard Mark 2 copper gauges and a range of the newer glass-fibre laminate or plastic gauges. Rainfall was recorded from June 1969 to September 1970. The total collection from each gauge was expressed as a percentage of a standard, and an estimate was made of the variability of catch for monthly and daily rainfall.

The overall characteristics of the copper rain-gauges and the newer types were very similar but the newer types collected more condensation (dew or hoar-frost). The 750-cm² gauge with rim at 30 cm collected more than one with rim at 45 cm which gave a catch comparable to that of a Mk 2 gauge at 30 cm. The Mk 2 gauge at 30 cm collected less than a Mk 2 with rim flush with an anti-splash surround. Two apparently identical versions of a commercially available gauge collected different amounts, probably because of a change in the slope of the exterior bevel below the edge of the rim. The field-calibrated 750-cm² tipping-bucket rain-gauges at Easthampstead, Filton, Glasgow Airport and Turnhouse collected overall about the same as or rather more than the Mk 2 standard rain-gauge.

Introduction. An ideal rain-gauge intercepts and collects all the liquid precipitation which would otherwise have fallen on the ground. In a practical, well-designed and well-exposed instrument, errors due to splash-in, splash-out and evaporation are made negligible. The remaining error is mainly an indirect result of turbulent wind flow over and within the collecting funnel of the gauge. This causes loss of catch because some of the raindrops which fall into the zone of turbulence immediately above the gauge are diverted over and out of the funnel. Such errors are a complex function of the wind speed at rain-gauge height, the raindrop size distribution and the shape of the above-ground part of the rain-gauge. On a perfectly uniform site, with surrounding trees, buildings, etc., located at a distance of more than about four times their height, it would not be expected that, for cumulative rainfall totals over reasonably long periods, there would be any difference between the true cumulative point rainfalls at different positions on such a site. However, when identical standard rain-gauges are exposed at different positions on a 'normal' site, their cumulative readings are found to be slightly but systematically different. These differences are considered to be due to small differences in the mean wind speed (during the precipitation) over the rims of the rain-gauges, brought about by small irregularities of exposure from one position to another on the normal site. Few normal sites are perfectly uniform all over — there are usually irregularities in the height of the ground; furthermore, some parts of a practical site may be slightly, but persistently, less sheltered from the mean wind prevailing during rainfall than other parts of the same site. Such site effects must be determined and taken into account when the performances of different types of rain-gauges positioned on the site are compared.

The site. On a site covering an area of approximately 100 ft by 30 ft (30 m × 9 m) at Easthampstead, Berkshire, an array of rain-gauges of various types has been set up. The site slopes downwards slightly from the north-east to the south-west, the height difference being about 1 ft; there are also minor undulations of a few inches between the gauges. The nearest building is 60 ft to the north-west, having a distance to height ratio of 5. The site is neither well sheltered nor unduly over-exposed, and is typical of the sort of location that in practice might be chosen for installing a standard rain-gauge for obtaining climatological rainfall data.

The rain-gauges. Standard 5-inch copper Mk 2 rain-gauges were installed with their rims at 30 cm above the ground at positions P9, P1, P4, P13, S1 and S2 as shown in Figure 1. The flush gauge marked in Figure 1 consisted of nine 5-inch Mk 2 gauges in a pit with a 'venetian-blind' type anti-splash surround. Two glass-fibre laminate 750-cm^2 collectors with their rims at 30 cm and at 45 cm were mounted at positions P2 and P6 respectively, whilst similar collectors with their rims at 45 cm, and fitted with tipping buckets and counters were installed at positions P5 and P12. Three 150-cm^2 glass-fibre conical collectors were mounted with their rims at 30 cm; that at P7 was straight-sided (SS), whilst those at P10 and P11 were slightly modified versions of this (SM). At P8 was a commercially available 150-cm^2 plastic collecting funnel (C). Photographs of some of these various rain-gauge collectors are available.

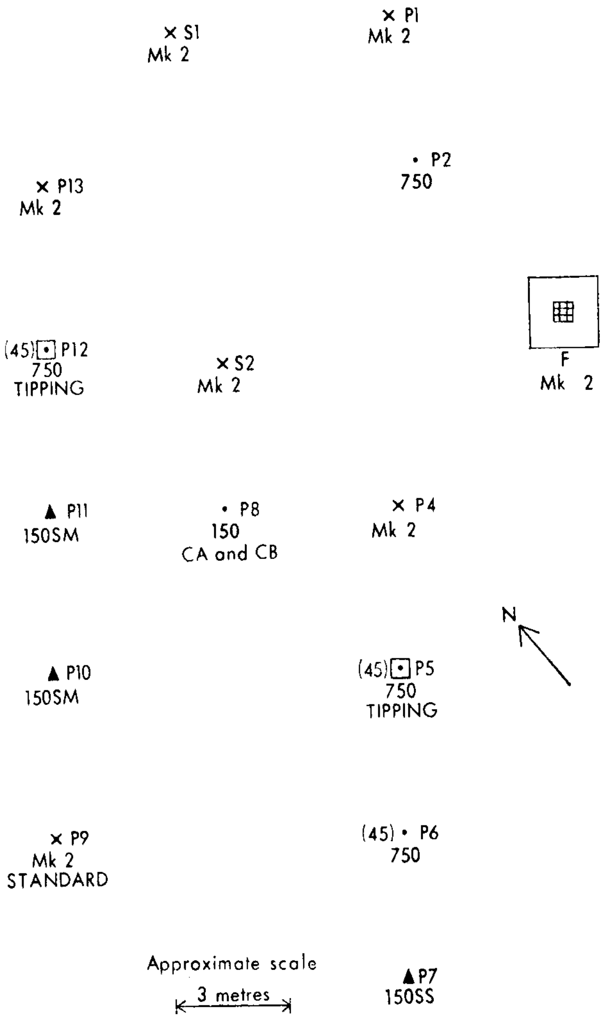


FIGURE 1—POSITIONS AND TYPES OF RAIN-GAUGES AT EASTHAMPSTEAD

(45) Height of rim (cm) of P5, P6 and P12, all others are 30 cm.

The measurements. Except for the gauges fitted with tipping buckets, the water in the collecting bottle of each rain-gauge was measured daily — but not during precipitation — in a 150-cm² collector measuring cylinder, and these measurements were tabulated. An amount registering below the 0·05 graduation in the cylinder was logged as a trace, and for some purposes counted as a reading of 0·025 graduations. The daily recorded measurements were then multiplied by the factors 1·000, 1·184 and 0·200 and rounded to the nearest 0·1 mm to obtain the daily rainfall in millimetres collected by the 150-cm², 5-inch and 750-cm² gauges respectively. Daily readings were taken from the centre rain-gauge of the nine Mk 2 rain-gauges forming the flush gauge. For the 750-cm² rain-gauges fitted with tipping buckets and counters, the number of tips shown by the counter was recorded daily. The buckets were calibrated *in situ* using a technique described fully in the installation instructions. In brief, rain-water is slowly run into the 750-cm² funnel from a burette and the volume required to cause the buckets to tip 12 times is measured. This volume, divided by 900 gives the calibration factor K, defined as the rainfall in millimetres equivalent to one tip. The buckets are designed and adjusted before installation for K to have a nominal value of 0·2 mm. For each of the 750-cm² tipping-bucket gauges at P5 and P12, K was determined from the mean of 12 tips on each of 5 separate occasions towards the beginning, in the middle and at the end of the trial period. The overall mean value of K for both gauges was found to be 0·207 mm, with a standard error of approximately 0·006 mm, or about 0·3 per cent.

Treatment of the data. Data representing occasions on which some or all of the precipitation fell as snow were ignored. Owing to the well-known uncertainty in the measurement by conventional rain-gauges of small quantities of precipitation and dew, data representing occasions on which less than 1 mm of precipitation was measured on the daily reading of the 5-inch Mk 2 rain-gauge at P9 were also ignored in the main analysis. This left rainfall measurements for each of the rain-gauges deployed, for each of a series of daily occasions on which 1 mm or more of rain fell. Each such occasion was called a rainfall event, and the number of these occurring in a stated period was designated by the letter n. The data were first examined by comparing the total rainfall collected by each of the gauges for all rainfall events which were common to the gauges being compared.

For all non-recording gauges except the straight-sided 150-cm² gauge at P7 and the 150-cm² gauge at P8, daily measurements started on 25 June 1969 and there were 116 common rainfall events for analysis up to 30 September 1970. The results of this analysis are in Table I*(a)*, wherein each gauge's total collection is expressed as a percentage of that collected in the flush gauge (F), in the standard 5-inch gauge at P9, and of the mean amount (MS) collected in the six standard 5-inch gauges. Similarly, in Table I*(b)* are analysed the 107 rainfall events common to all the non-recording gauges in the period from 22 August 1969 to 30 September 1970. However, the 150-cm² collector (CA) which was at P8 from 22 August 1969 until 12 June 1970 was replaced on 13 June 1970 by an externally apparently identical model (CB), in which the interior collecting surface was bowl-shaped rather than funnel-shaped. On careful examination, however, the external details were found in fact to be very slightly different; the discontinuity between the metal knife-edged rim and the adjacent plastic flange was slightly greater,

TABLE I—COMPARISON OF RAIN-GAUGES AT EASTHAMPSTEAD FOR RAIN DAYS EACH WITH AT LEAST 1 mm MEASURED IN THE 5-INCH STANDARD RAIN-GAUGE AT P9

		(a) 25 June 1969 to 30 September 1970, $n = 116$				(b) 22 August 1969 to 30 September 1970, $n = 107$			
	Site position	Rainfall *mm*	Per cent of F	Per cent of P9	Per cent of MS	Rainfall *mm*	Per cent of F	Per cent of P9	Per cent of MS
150 cm²									
CA	P8	—				} 574·6	101·26	105·59	106·27
CB	P8	—							
SS	P7	—				547·4	96·17	100·27	100·92
SM	P10	670·5	95·95	99·45	100·10	543·2	95·43	99·51	100·15
SM	P11	676·9	96·87	100·40	101·06	548·4	96·35	100·46	101·11
750 cm²									
Rim at 30 cm	P2	685·6	98·11	101·69	102·36	557·3	97·91	102·09	102·75
Rim at 45 cm	P6	677·9	97·01	100·55	101·21	550·1	96·64	100·77	101·42
5 inch									
Flush	F	698·8	100·00	103·65	104·33	569·2	100·00	104·27	104·94
Standard	P9	674·2	96·48	100·00	100·66	545·9	95·91	100·00	100·65
Standard	P1	666·9	95·44	98·92	99·57	540·6	94·98	99·03	99·67
Standard	P4	669·8	95·85	99·35	100·00	542·8	95·36	99·43	100·07
Standard	P13	672·5	96·24	99·75	100·40	544·9	95·73	99·82	100·46
Standard	S1	666·7	95·41	98·89	99·54	539·1	94·71	98·75	99·39
Standard	S2	668·8	95·71	99·20	99·85	541·1	95·06	99·12	99·76
Mean standard	MS	669·8	95·85	99·35	100·00	542·4			
Standard deviation		3·0				2·6			
Coefficient of variation		0·5%				0·5%			

n = number of rainfall events

and this flange was about 2° more nearly vertical. The performances of these two versions of the 150-cm² gauge at P8 were found to be different; consequently the combined data for the two versions in Table I*(b)* are shown bracketed in the first line, and the table is subdivided into Table II *(a)*, which covers the 76 rainfall events common to the CA and the other gauges in the period 22 August 1969 until 12 June 1970, and Table II *(b)* which analyses the 31 rainfall events from 13 June until 30 September 1970 during which the 150-cm² collector CB was at P8.

The distant-reading tipping-bucket rain-gauges at P12 and P5 were not installed until 2 December 1969; thereafter there were 71 rainfall events when both tipping-bucket gauges were functioning together with the other 750-cm² and standard 5-inch collectors, and these are analysed in Table III.

Discussion. For the six identical 5-inch rain-gauges at P9, P1, P4, P13, S1 and S2 the ratio of the standard deviation to the mean amount collected, i.e. the coefficient of variation, was 0·5 per cent. Applying the value of 2·57 for Student's t for 5 degrees of freedom, it follows that it would be expected that, owing to site effects (see Introduction), on not more than 5 per cent of occasions would the total in a standard 5-inch gauge placed at random on the site differ from the mean total collected by the standard 5-inch gauges by more than $\pm$ 2·57 $\times$ 0·5 = $\pm$ 1·3 per cent. Any gauge on the site which shows a departure of more than 1·3 per cent from the mean of the 5-inch gauges may be regarded as having significantly different collection characteristics from the standard gauge. That is, the significantly above, or below, normal ratio for such a gauge is to be ascribed to the gauge itself, rather than to the particular position it occupies on the site.

On this basis, then, it may be seen from the 'per cent of MS' columns in Tables I–III that the flush gauge, the 150-cm² collector CA and the 750-cm² funnel with rim at 30 cm collected significantly more rain than would have been expected from a 5-inch Mk 2 rain-gauge with rim at 30 cm in the same position, while the tipping-bucket rain-gauge at P5 collected significantly less.

Raising the rim height of the 750-cm² collector by 15 cm to 45 cm above the ground evidently reduces the significant over-collection of this gauge by 1–1½ per cent; at 45 cm the 750-cm² funnel collects an amount insignificantly different from the mean amount collected by the standard 5-inch rain-gauges.

As the design and rim height of the standard 5-inch Mk 2, the flush and the 750-cm² glass-fibre rain-gauges are such as effectively to eliminate errors due to splash-in of rain-water from the surrounding ground or from the outer sides of these gauges, it follows that the shape and size of the 750-cm² collectors, and the exposure with rim at ground level of the flush gauge are rather more effective than that of the standard Mk 2 rain-gauge in reducing losses of catch due to wind and turbulence effects. Other investigations have also shown a relatively high efficiency of catch for flush gauges with effective anti-splash surrounds.

However, although the collector CB behaved indistinguishably from a standard Mk 2 rain-gauge (Table II*(b)*), the CA version overall collected some 5 per cent more than even the flush gauge (Table II*(a)*). It is believed that the slightly nearer to horizontal inclination of the wide bevel just below the rim, together with the smaller obstruction created by the reduced gap

TABLE II—COMPARISON OF RAIN-GAUGES AT EASTHAMPSTEAD SEPARATED INTO TWO PERIODS (*a*) IN WHICH GAUGE CA WAS USED AND (*b*) IN WHICH GAUGE CB WAS USED

		(*a*) 22 August 1969 to 12 June 1970, $n = 76$				(*b*) 13 June to 30 September 1970, $n = 31$			
	Site position	Rainfall *mm*	Per cent of F	Per cent of P9	Per cent of MS	Rainfall *mm*	Per cent of F	Per cent of P9	Per cent of MS
150 cm^2									
CA	P8	377·6	104·68	109·42	110·05	—		—	—
CB	P8	—	—	—	—	198·8	95·35	99·00	99·75
SS	P7	349·2	96·81	101·19	101·78	198·2	95·06	98·71	99·45
SM	P10	343·2	95·15	99·45	100·03	200·0	95·92	99·60	100·35
SM	P11	347·2	96·26	100·61	101·19	201·2	96·50	100·20	100·95
750 cm^2									
Rim at 30 cm	P2	353·0	97·86	102·29	102·88	204·3	97·99	101·74	102·51
Rim at 45 cm	P6	348·1	96·51	100·87	101·46	202·1	96·93	100·65	101·40
5 inch									
Flush	F	360·7	100·00	104·52	105·13	208·5	100·00	103·83	104·62
Standard	P9	345·1	95·67	100·00	100·58	200·8	96·31	100·00	100·75
Standard	P1	342·3	94·90	99·19	99·77	198·3	95·11	98·75	99·50
Standard	P4	343·7	95·29	99·59	100·17	199·1	95·49	99·15	99·90
Standard	P13	344·4	95·48	99·80	100·38	200·5	96·16	99·85	100·60
Standard	S1	340·4	94·37	98·64	99·21	198·8	95·35	99·00	99·75
Standard	S2	342·7	95·01	99·30	99·88	198·4	95·16	98·80	99·55
Mean standard	MS	343·1	95·12	99·42	100·00	199·3	95·59	99·25	100·00
Standard deviation		1·7				1·1			
Coefficient of variation		0·5%				0·5%			

n = number of rainfall events

TABLE III—COMPARISON OF RAIN-GAUGES AT EASTHAMPSTEAD FOR THE PERIOD IN WHICH THE TWO DISTANT-READING TIPPING-BUCKET RAIN-GAUGES WERE INSTALLED, 2 DECEMBER 1969 TO 29 SEPTEMBER 1970

	Site position	Rainfall	Per cent of F	Per cent of P9	Per cent of MS
750 cm^2		*mm*			
Rim at 30 cm	P2	386·7	97·50	101·90	102·74
Rim at 45 cm	P6	381·0	96·07	100·40	101·22
At 45 cm with tipping bucket	P12	372·4	93·90	98·13	98·94
At 45 cm with tipping bucket	P5	361·0	91·02	95·13	95·91
5 inch					
Flush	F	396·6	100·00	104·51	105·37
Standard	P9	379·5	95·69	100·00	100·82
Standard	P1	375·0	94·55	98·81	99·63
Standard	P4	376·7	94·98	99·26	100·08
Standard	P13	378·4	95·41	99·71	100·53
Standard	S1	373·6	94·20	98·45	99·26
Standard	S2	375·2	94·60	98·87	99·68
Mean standard	MS	376·4	94·91	99·18	100·00
Standard deviation		2·2			
Coefficient of variation		0·6%			

Number of events = 71

between bevel and rim of the CA model allowed raindrops coalescing after impact with the windward side of this bevel to be blown upwards across the small obstruction, over the knife-edged rim, and into the gauge. Whatever the explanation, the results show that a visually almost undetectable change in the shape and design of a rain-gauge collector can have a large influence on its efficiency, and that exterior outward-sloping surfaces below the knife-edge rims are liable to cause errors due to splash-in or blow-in.

The 750-cm^2 tipping-bucket rain-gauge at P5 registered significantly less rainfall than its counterpart at P12 (Table III). However, several failures of the counter on the gauge at P5 occurred. Rainfall events during which the P5 counter was positively known to be inoperative have not been included in the comparative data in Table III. Nevertheless, it is probable that on some rainfall events included in this table, tips of the buckets had occurred but not been registered on the counter before it became obvious that the counter had failed. For this reason, the data for the tipping-bucket rain-gauge at P5 are regarded as suspect, and are not considered further. The cause of the counter defects has since been diagnosed.

In Table III the difference between the cumulative rainfall collected by the 750-cm^2 funnel at 45 cm at P6 and that registered by the similar collector at 45 cm at P12, but fitted with a tipping bucket, of 2·3 per cent is unlikely to be due to the chance effect of the positions chosen for these two gauges on the site. The apparent overall loss of up to about 2 per cent when the rainfall is metered by the tipping-bucket device rather than collected in a bottle may be due to the cumulative effect of evaporation from a partially filled bucket between successive rainfall events. To minimize any small loss due to evaporation, a shallow tray, normally automatically containing a layer of water through discharge from the tipping buckets, can be fitted at the base of the support tube; this maintains a near-saturated atmosphere around the buckets in the support tube between rainfall events. However, an anti-evaporation tray should not be used unless the tipping-bucket rain-gauge is also fitted with an anti-condensation shield, for reasons which follow later.

For cumulative rainfall events totalling around 400 mm or more, where each event is defined as a 24-hour rainfall of at least 1 mm, the ratios in Tables I–III show that the glass-fibre 150-cm^2 gauges with rims at 30 cm and the 750-cm^2 tipping-bucket rain-gauge with rim at 45 cm collect within 1·2 per cent of the mean of the standard 5-inch gauge. However, the ratios found will not necessarily be valid for other periods in which the average wind, turbulence and raindrop size distribution during precipitation may not be the same. Neither will they necessarily apply at other locations where again the exposure and wind régime may be different. Without many years of data, it does not seem possible to calculate the standard error or the confidence limits which would serve as a measure of the reproducibility of these ratios for large aggregate amounts such as annual rainfall. From the work of Poncelet, involving five years of data, it can be estimated that the standard error of ratios for conventional rain-gauges derived from one year's aggregate rainfall is about 1 per cent. At Easthampstead, the ratios could also differ by about 1 per cent depending on the exact spot chosen on a given suitable site to install the standard 5-inch reference gauge. So, for measuring rainfall in the U.K. for long-period climatological purposes, a change of reference rain-gauge from the 5-inch Mk 2 copper gauge to the 150-cm^2 glass-fibre or to the 750-cm^2 collector at 45 cm with calibrated tipping buckets is unlikely to introduce any additional systematic errors in mean annual or longer-period rainfall statistics.

Although difficult to maintain as a network rain-gauge, there is little doubt that rainfall measured by a carefully looked after flush gauge with proper anti-splash surround is a closer approach to the true rainfall than that measured in a standard rain-gauge with rim exposed above the ground, and unprotected by a turf wall. Where, for hydrological or other special purposes, best estimates of true annual point rainfall are required and it has not been feasible to have a flush or turf-wall gauge installed and maintained, it might be desirable to increase the annual rainfall as measured in a standard gauge exposed at 30 cm by some percentage increment C. For aggregates of daily falls equalling or exceeding 1 mm in the year 25 June 1969–30 June 1970 at Easthampstead, Table I indicates that the appropriate value for C is about 4 per cent. For the aggregate of all occasions of daily measured rainfall exceeding a trace (excluding snow) in the two-year period May 1968–April 1970 at Kew, C is 7 per cent. If F is the monthly rainfall measured in the flush gauge at Kew, and S that in the nearby standard rain-gauge, then the regression equation of F on S for the 24 months of available data, with S ranging from 2·9 mm (September 1969) to 123·7 mm (September 1968) is :

$$F = 1{\cdot}05S + 1{\cdot}09 \pm 2{\cdot}0 \text{ (S.E.)},$$

where S.E. is the standard error.

For the mean monthly rainfall of 52·09 mm measured at Kew in the standard 5-inch gauge over this period, the most probable measurement in the flush gauge calculated from the above regression equation would be 55·78 $\pm$ 2·0 mm (S.E.), or 107·0 per cent $\pm$3·6 per cent (S.E.) of that in the standard gauge. Thus, the standard error of the correction factor C for Kew is in magnitude about half that of the factor itself, so that applying a correction factor to a particular month's rainfall measured by a standard rain-gauge might introduce as large an error as it was intended to remove. For aggregation over years, rather than 30 days, the factor is likely to be much more stable, though variations of at least 1 per cent from year to year are to be expected.

Dew collection. On radiation nights, the amount of condensation on the collecting surfaces of the glass-fibre rain-gauges is likely to be greater than on copper Mk 2 rain-gauges, where surfaces will be maintained at a higher equilibrium temperature owing to better conduction of heat from the ground in which the copper base of these rain-gauges is embedded. This expectation is borne out by results over the period 22 August 1969–13 November 1969, chosen purposely because it included many clear, calm nights with heavy dewfall. For cumulative collections of daily amounts of less than 1 mm (mostly dew), counting traces as each equivalent to 0·025 mm, over this period the ratio of the mean amount collected in the five glass-fibre gauges to the mean of the six copper gauges was 136·2 per cent, whereas in the same period for amounts equalling or exceeding 1 mm (mostly rain) the ratio was 102·5 per cent. However, on the 'less than 1 mm' occasions, not all the water collected in the bottles came from dew which had formed on the exposed outer collecting surfaces of the glass-fibre funnels. Appreciable quantities of condensation droplets have been seen to have formed on the interior surfaces of these funnels on radiation nights; the drops could amalgamate and run down into the collecting bottles or be metered through the tipping buckets. A laboratory experiment was carried out to determine the possible rate of accumulation of this interior condensation. The open lower end of the support tube of a 750-cm^2 rain-gauge was left standing in a sink of water at 18–19°C, so maintaining a near-saturated atmosphere within the interior of the rain-gauge. The exit of the collecting-funnel spout was sealed, and the funnel maintained full of crushed ice. Under these ideal conditions for maximum interior condensation, a spurious dewfall of 0·14 mm was collected in the bottle in 6 hours. A collection of interior condensation at half this rate for 8 hours during each of the 24 or so radiation nights which occurred in the period 22 August 1969–13 November 1969 would have accounted for the additional 34 per cent collected by the glass-fibre rain-gauges in this period.

In the U.K. the fraction of the annual, or longer-period, total measured precipitation which constitutes dew is rather small, so that in this context the additional amounts of spurious dew collected by glass-fibre rain-gauges is probably negligible. But for monthly or shorter periods of rainfall, dew may sometimes form a significant part of the total measured precipitation. Where glass-fibre rain-gauges are to be used for measuring monthly or shorter periods of rainfall, or where they are to be used with a tipping-bucket device and anti-evaporation tray in the support tube, a condensation deflector can be fitted to the interior of the funnel. This deflector is so designed as effectively to divert droplets running down the interior of the funnel and spout from passing into the collecting bottle or the tipping bucket.

Performance of tipping-bucket rain-gauges. In addition to the daily measurements from the rain-gauges at Easthampstead, data were also available from 750-cm^2 tipping-bucket and adjacent 5-inch standard rain-gauges read six times a day at three of the outstations (Bristol/Filton, Glasgow Airport and Edinburgh/Turnhouse Airport) where tipping-bucket rain-gauges are in operational use for reporting hourly rainfall amounts. An analysis of these data is contained in Table IV, in which N stands for the

TABLE IV—PERFORMANCE OF TIPPING-BUCKET RAIN-GAUGES AT OUTSTATIONS

Station	Period	N_1	N_2	N_3	G_1	G_2	G_3	T_1 and T_2	T_3	R_1	R_2	R_3
Filton	Nov. 1969	40	2	31	81·1	81·15	80·0	80·79	79·37	99·62	99·56	99·22
	Dec.	49	5	33	53·6	53·73	52·3	52·98	51·16	98·85	98·62	97·81
K = 0·203 mm/tip	Jan. 1970	72	8	47	93·6	93·80	91·9	92·16	89·73	98·46	98·25	97·63
Rim height 30 cm	Feb.	48	7	30	57·8	57·98	56·6	57·45	55·42	99·39	99·09	97·91
	Mar.	37	8	18	25·0	25·20	23·5	26·19	23·55	104·75	103·92	100·20
	Apr.	52	5	32	53·4	53·53	51·5	55·01	52·58	103·02	102·78	102·09
	May	27	5	17	37·4	37·53	36·7	37·76	36·95	100·96	100·62	100·67
	June	29	5	21	47·6	47·73	47·2	46·49	46·08	97·66	97·41	97·63
	July	35	3	25	70·5	70·58	68·1	70·24	68·82	99·63	99·52	101·05
	Aug.	46	12	26	53·9	54·20	52·5	51·77	50·14	96·04	95·51	99·51
	Sept.	27	3	23	85·0	85·08	84·4	85·46	84·24	100·54	100·45	99·81
	Oct.	40	5	29	30·1	30·22	28·5	30·25	27·81	100·49	100·07	97·58
	Nov. '69–Oct. '70	502	68	332	689·0	690·70	673·2	686·55	665·85	99·64	99·40	98·91
	1970											
Turnhouse	15 Dec.–14 Jan.	29	26	20	35·5	36·15	34·1	37·54	34·27	105·74	103·83	100·50
	15 Jan.–14 Feb.	84	33	35	44·2	45·03	42·5	46·51	42·43	105·23	103·30	99·84
K = 0·204 mm/tip	15 Feb.–14 Mar.	65	34	20	39·7	40·55	38·1	41·82	38·76	105·34	103·13	101·73
Rim height 30 cm	15 Mar.–14 Apr.	70	38	24	25·5	26·45	24·8	29·99	27·54	117·60	113·38	111·05
	15 Apr.–14 May	85	51	20	38·2	39·48	35·9	41·00	36·92	107·33	103·86	102·85
	15 May–14 June	54	37	9	12·3	13·23	10·9	14·28	12·24	116·10	107·98	112·29
	15 Dec.–14 June	387	219	128	195·4	200·88	186·3	211·14	192·16	108·06	105·10	103·15
	1970											
Glasgow Airport	15 Dec.–14 Jan.	35	11	23	59·2	59·48	57·4	59·99	57·17	101·34	100·87	99·59
	15 Jan.–14 Feb.	98	32	53	90·4	91·20	87·7	92·92	89·69	102·79	101·89	102·27
K = 0·202 mm/tip	15 Feb.–14 Mar.	64	23	26	53·5	54·08	51·0	56·56	52·72	105·72	104·60	103·38
Rim height 45 cm	15 Mar.–14 Apr.	85	46	29	47·3	48·45	45·6	51·51	48·68	108·90	106·32	106·75
	15 Apr.–14 May	79	35	31	76·2	77·08	74·4	78·98	76·36	103·65	102·47	102·63
	15 May–14 June	40	28	9	24·8	25·50	24·4	27·47	27·07	110·77	107·73	110·93
	15 Dec.–14 June	401	175	171	351·4	355·78	340·5	367·43	351·69	104·56	103·27	103·29

N Number of pairs of rain-gauge readings. G Aggregate of readings from the nearby standard 5-inch rain gauge.

T Corresponding totals registered by the tipping-bucket rain-gauge. R Percentage ratio of tipping-bucket to standard 5-inch rainfall totals.
Suffix 1 — Traces ignored. Suffix 2 — Each of N_2 trace readings is counted as 0·025 mm of rain. Suffix 3 — In each pair of readings more than 0·2 mm was read in the 5-inch rain-gauge.

K Calibration constant.

number of pairs of rain-gauge readings, G the aggregate of readings from the nearby standard 5-inch rain-gauge, T the corresponding totals registered by the tipping-bucket rain-gauge, and R the percentage ratio of tipping-bucket to standard 5-inch rainfall totals.

When the cumulative rainfall is obtained by summing the readings obtained from a 5-inch rain-gauge read and emptied six times a day, the total is likely to be an underestimate if individual trace readings, that is, readings of less than 0·05 mm of rain, are ignored. Because all amounts of precipitation, however small, pass into, and in aggregate are metered by, the tipping buckets, the ratio of tipping-bucket to 5-inch rain-gauge totals will be greater when traces recorded in the 5-inch gauge are ignored than when an appropriate rainfall equivalent, such as 0·025 mm, is accorded to them. In Table IV, suffix 1 refers to data where traces have been ignored, suffix 2 to readings, aggregates and ratios where each of the N_2 trace readings has been counted as equivalent to 0·025 mm of rain, and suffix 3 to ratios and aggregates derived from the N_3 pairs of readings in each of which more than 0·2 mm was read in the 5-inch gauge. Where, as at Filton, the average number of trace readings per month was only about six, the difference between the overall ratios R_2 (counting traces as 0·025 mm) and R_1 (ignoring traces) is no more than 0·2 per cent. At Turnhouse, however, where trace readings were recorded about six times more often, the difference amounts to 3 per cent.

The problem of how to deal with trace readings in the standard gauge when evaluating aggregate total measured rainfall for that gauge for comparison with the total rainfall that has been counted as having passed through a tipping-bucket gauge is largely removed when, as in Tables III and V*(a)*, only occasions when the daily fall in the 5-inch gauge exceeds 1 mm are aggregated. For data obtained from standard gauges read six times daily, such as in Table IV, the problem is similarly largely overcome by only aggregating individual readings of more than 0·2 mm. The figures in columns headed with a suffix 3 in Table IV refer to such data. It can be seen that overall the tipping-bucket rain-gauge at Filton, with a field calibration of 0·203 mm per tip, registered 98·9 per cent of the rainfall in the nearby standard 5-inch rain-gauge, the same as the 98·9 per cent registered by the instrument at P12 at Easthampstead (Table III) in relation to the mean of the nearby six standard rain-gauges there. However, the rim of the Filton 750-cm^2 collector is mounted at 30 cm, whereas that at Easthampstead was at 45 cm. Table IV shows the overall ratios for the Turnhouse and Glasgow tipping-bucket gauges were much the same, at 103·2 per cent and 103·3 per cent respectively, despite the rim of the former's being at 30 cm and the latter's at 45 cm. Bearing in mind that these ratios are bound to vary to some extent from one climatic régime to another, the results indicate that at least for measuring large overall amounts of rain the tipping-bucket rain-gauge is as efficient as, or perhaps slightly more efficient than, the standard Mk 2 manually read gauge.

Variability for monthly rainfall. The mean of the 12 monthly ratios R_3 for Filton is 99·3 per cent and the standard deviation about this mean is 1·5 per cent, with extreme departures of +2·7 per cent in April and −1·6 per cent in January, June and October 1970. The regression equation of T_3 on G_3 for the 12 months of data for Filton in Table IV is :

$$T_3 = 0{\cdot}99\, G_3 + 0{\cdot}03 \pm 1{\cdot}1 \text{ (S.E.)}.$$

TABLE V(a)—VARIABILITY OF RAIN-GAUGES AT EASTHAMPSTEAD FOR DAILY RAINFALL*

Comparative rain-gauge	Site position	Data period	N	E	P per cent
5 inch					
Standard	S2	25/6/69–30/6/70	89	$Y = 0.997S - 0.016 \pm 0.293$	99.5 ± 2.9
Standard	P4	25/6/69–30/6/70	89	$Y = 0.992S + 0.013 \pm 0.265$	99.4 ± 2.6
Flush	F	25/6/69–30/6/70	89	$Y = 1.009S + 0.146 \pm 0.486$	102.4 ± 4.9
750 cm^2					
Rim at 30 cm	P2	25/6/69–30/6/70	89	$Y = 1.001S + 0.092 \pm 0.394$	101.0 ± 3.9
Rim at 45 cm	P6	25/6/69–30/6/70	89	$Y = 0.999S + 0.039 \pm 0.339$	100.3 ± 3.4
Rim at 45 cm	P6	2/12/69–30/6/70	57	$Y = 0.999S + 0.017 \pm 0.310$	100.1 ± 3.1
Rim at 45 cm with tipping bucket ($K = 0.207$ mm/tip)	P12	2/12/69–30/6/70	57	$Y = 0.977S + 0.081 \pm 0.451$	98.5 ± 4.5
150 cm^2					
SM	P11	22/8/69–12/6/70	76	$Y = 1.012S - 0.025 \pm 0.276$	100.9 ± 2.8
CA	P8	22/8/69–12/6/70	76	$Y = 1.075S + 0.085 \pm 0.724$	108.4 ± 7.2

Y Amount collected in comparative rain-gauge. S Amount collected in standard 5-inch rain-gauge at P9.
N Number of daily rainfalls each measuring at least 1 mm in the standard rain-gauge at P9.
E Regression equation of Y on S for daily rainfalls, $\pm$ the 95 per cent confidence limits of Y.
P Most probable percentage ratio Y/S, $\pm$ the 95 per cent confidence limits, for a rainfall of 10 mm in the standard rain-gauge.
K Calibration constant.

TABLE V(b)—VARIABILITY OF 750-cm^2 TIPPING-BUCKET RAIN-GAUGES AT OUTSTATIONS FOR DAILY RAINFALL*

Location of 750-cm^2 tipping-bucket rain-gauge	h cm	K mm/tip	Data period	N	E	P per cent
Turnhouse	30	0.204	15/12/69–15/6/70	45	$Y = 0.989S + 0.202 \pm 0.449$	100.9 ± 4.5
Glasgow Airport	45	0.202	15/12/69–15/6/70	60	$Y = 1.030S + 0.004 \pm 0.892$	103.0 ± 8.9
Filton	30	0.203	6/11/69–31/8/70	100	$Y = 0.966S + 0.127 \pm 0.742$	97.9 ± 7.4

Y Amount collected in 750-cm^2 tipping-bucket rain-gauge. S Amount collected in nearby standard 5-inch rain-gauge.
h Height of rim above ground.
K Calibration constant.
N Number of daily rainfalls each totalling at least 1 mm in the nearby standard rain-gauge, where each daily rainfall is the aggregate of measurements exceeding a trace made at 3- or 6-hourly intervals.
E Regression equation of Y on S for daily rainfalls, $\pm$ the 95 per cent confidence limits of Y.
P Most probable percentage ratio Y/S, $\pm$ the 95 per cent confidence limits, for an aggregate daily rainfall of 10 mm in the standard rain-gauge.

* Rain days each with a total of at least 1 mm measured in the standard 5-inch rain-gauge (P9 at Easthampstead, nearby at outstations).

For the mean monthly value of G_3 of 56·1 mm, the most probable value that would have been recorded by the tipping bucket, calculated from the above regression equation, is 55·5 mm $\pm$1·1 mm (S.E.) or 98·9 per cent $\pm$2·0 per cent (S.E.) of G_3. Thus it appears that the ratio for any particular month at Filton can be expected to depart from the overall value by more than $\pm$2 per cent in 3 or 4 months in the year. But the variability of the monthly values of the ratio must depend on the variability of the monthly climatic régimes, and 12 months are probably insufficient to sample this adequately. Furthermore, for a month with very low rainfall, the value of the ratio has but little significance. Although there are only 6 months' data available for each of the stations in Scotland, at all three stations there is an indication that the ratio may tend to have a maximum value in the early summer months, and a minimum in the winter months.

Variability for daily rainfall. Clearly the performance of a rain-gauge cannot be regarded as acceptable solely on the basis that overall it collects close to 100 per cent of the rainfall measured in a standard gauge; it is necessary also to be assured that for individual small totals such as typically are measured during an average wet day the departures from the overall 100 per cent figure are not normally excessive.

To derive a relative measure of the extent of variation in the ratio of the amount Y collected by a particular rain-gauge to the amount S measured in a nearby standard rain-gauge for daily rainfall events, the regression equation of Y on S was calculated for the various rain-gauges shown in Tables V *(a)* and *(b)* for all daily rainfall totals of amounts of 1 mm or more in the standard gauge, and from the residual sum of squares the 95 per cent confidence limits of the regression were computed. Considering a rain day on which 10 mm of rain were measured in the standard 5-inch gauge, the amount Y that most probably would have been measured by a comparative gauge was calculated using the appropriate regression equation, and the percentage ratio of this amount to the 10 mm in the standard gauge was derived, with the 95 per cent confidence limits of this ratio. These ratios and their 95 per cent confidence limits are expressed in column P of Tables V *(a)* and *(b)*, and serve as an index of the variability of the various rain-gauges' relative collection efficiencies for a typical (rather heavy) day's rainfall. The smaller these confidence limits are, the more precise and reproducible are the daily rain-gauge measurements compared with those of a standard 5-inch rain-gauge.

The minimum attainable value for the confidence limits is set by the variability of the measurements from one standard rain-gauge compared with those from another nearby; if the rain-gauges being compared are identical in shape and exposure, this 'natural' variability cannot be reduced by altering their shape or design. From Table V *(a)*, containing the results for rain-gauges at Easthampstead, it can be seen that, relative to the standard 5-inch gauge at P9, the identical 5-inch rain-gauges at S2 and P4 have the lowest variability, at between 2½ and 3 per cent, and this standard is also attained by the 150-cm^2 rain-gauge at P11. The 750-cm^2 collectors are slightly more variable, with confidence limits between 3 and 4 per cent, while the flush gauge and the tipping-bucket gauge at Easthampstead collect within 4½ to 5 per cent of the expected ratio. Increasing the height above the ground of the rim of the 750-cm^2 collector from 30 cm to 45 cm does not increase its variability.

while including a tipping-bucket device to meter the rain-water rather than collecting and measuring it from a bottle makes the 750-cm² rain-gauge about 1½ per cent less consistent, with 95 per cent confidence limits of $\pm 4{\cdot}5$ per cent. The 750-cm² tipping-bucket rain-gauge is incapable of discriminating to within ± 1 tip, or for a rainfall of 10 mm to within ± 2 per cent, corresponding to a 95 per cent confidence limit of $\pm 1{\cdot}3$ per cent. Thus, erratic tipping of the buckets due to friction in the bearings, etc., contributes insignificantly to the total variability of the tipping-bucket rain-gauge.

The large range of $\pm 7{\cdot}2$ per cent for the confidence limits of the 150-cm² rain-gauge CA is no doubt due to the varying incidence of errors due to splash-in or blow-in, as already discussed.

Table V *(b)* contains a similar analysis of the outstation tipping-bucket rain-gauge performance from the point of view of ratio variability. However, each day's rainfall equalling or exceeding 1 mm in the 5-inch gauge was not obtained from a single once-daily reading, as at Easthampstead, but was the aggregate of six readings, some of which could have been of a trace. The traces were ignored in obtaining the daily aggregate of the 5-inch gauge readings; consequently the ratios and the variabilities in Table V *(b)* can be expected to be slightly greater than those for the Easthampstead tipping-bucket rain-gauge in Table V *(a)*, to an extent dependent on the frequency and regularity of occurrence of trace readings at these outstations on occasions of aggregate daily rainfalls of 1 mm or more. In fact the range of the 95 per cent confidence limits for the ratio at Filton and at Glasgow is about 3 or 4 per cent greater than that found for the tipping-bucket rain-gauge at Easthampstead. Nevertheless, even at Glasgow, on 95 per cent of occasions of a daily rainfall aggregating 10 mm, the amount registered by the nearby 750-cm² tipping-bucket rain-gauge with rim at 45 cm above the ground would not lie outside the range 11·2–9·4 mm. Random errors (relative to a standard rain-gauge) giving this range of daily rainfall are probably acceptable for the purposes to which measurements of daily rainfall are put.

Conclusions. Some general conclusions which follow from these trials and analyses are :

(i) The Meteorological Office 150-cm² and 750-cm² glass-fibre funnels are in general indistinguishable from the Mk 2 copper rain-gauges in their overall collection characteristics; they do, however, collect more condensation precipitation (dew or hoar-frost), especially if not fitted with anti-condensation shields.

(ii) The Mk 2 5-inch rain-gauge itself collects less rainfall when its rim is at the standard height of 30 cm above the ground than when mounted flush with an anti-splash surround.

(iii) Two outwardly almost identical versions of a commercially available 150-cm² rain-gauge have markedly different performance characteristics.

(iv) The field-calibrated 750-cm² tipping-bucket rain-gauges, with rims at 30 cm or 45 cm, collect overall about the same as, or rather more than, the Mk 2 standard rain-gauge; they are proving reasonably reliable in the field, but their collection efficiency when measuring daily rainfall is rather variable. However, where a daily-read standard climatological rain-gauge is installed nearby, the rainfall over intermediate periods within the day obtained from a tipping-bucket gauge fitted with a counter or event recorder may readily be apportioned to ensure that the daily aggregate agrees with that measured by the standard gauge.

OBITUARY

It is with regret that we record the death on 29 April 1971 of Mr J. B. Anderson, Experimental Officer, Met. O. 7.

REVIEW

Seventh annual report of the Water Resources Board, presented by the Water Resources Board, Reading. 245×150 mm, pp. vii+104, *illus.*, H.M. Stationery Office, London, 1971. Price: 70p.

The successive annual (and other) reports issued by the Water Resources Board at Reading, since that organization came into being following the Water Resources Act 1963, have always been of interest to those in the Meteorological Office who are in any substantial sense concerned with hydrometeorology. Very close links have in fact been established between certain groups on the staff of the Board and within the Office, and it is more than likely that those links will be continuously strengthened in the future. (It naturally follows that the Office is normally mentioned in the annual reports of the Board and vice versa.)

The present report is of quite exceptional interest because of what it says about the future in the context of water resources management and its organization at the national and regional levels. The final chapter out of seven and 4 of the 15 appendices, totalling in numbers of pages very slightly more than a quarter of the printed text and tables, are directly relevant to this matter, whilst some other parts of the report, in particular Chapter 5 on (present) Research, are of course by no means entirely irrelevant.

The occasion for such emphasis on future organization is that the Central Advisory Water Committee is due to report soon on this very big problem, and during the year under review the Water Resources Board was among those (one must assume very prominently) who submitted papers and discussed them with the Committee. The Water Resources Board is in no doubt at all about how much needs to be done to consolidate and advance the very big step forward achieved through the Water Resources Act 1963, and also in no doubt about how soon all this needs to be done. The writing is direct and forceful, the recommendations are firm and completely unambiguous, and the result is good pleasurable reading, highly recommended to all, compulsory for many.

To take a small but significant example: on page 50 in a specific recommendation on a financial need, there occurs the beautifully straightforward phrase 'for dealing with dirty water'. A report of lesser calibre might have worried like a neurotic mongrel at 'monitoring, evaluation and regulation of dangerous or unacceptable levels of pollution', taking more than twice the length to drive home less than half the meaning. It would be wrong to give anyone a valid excuse for not reading this report, and the sample quotations from Chapter 7 which follows are not intended to provide a major helping of the real meat, but only a sniff at its flavour :

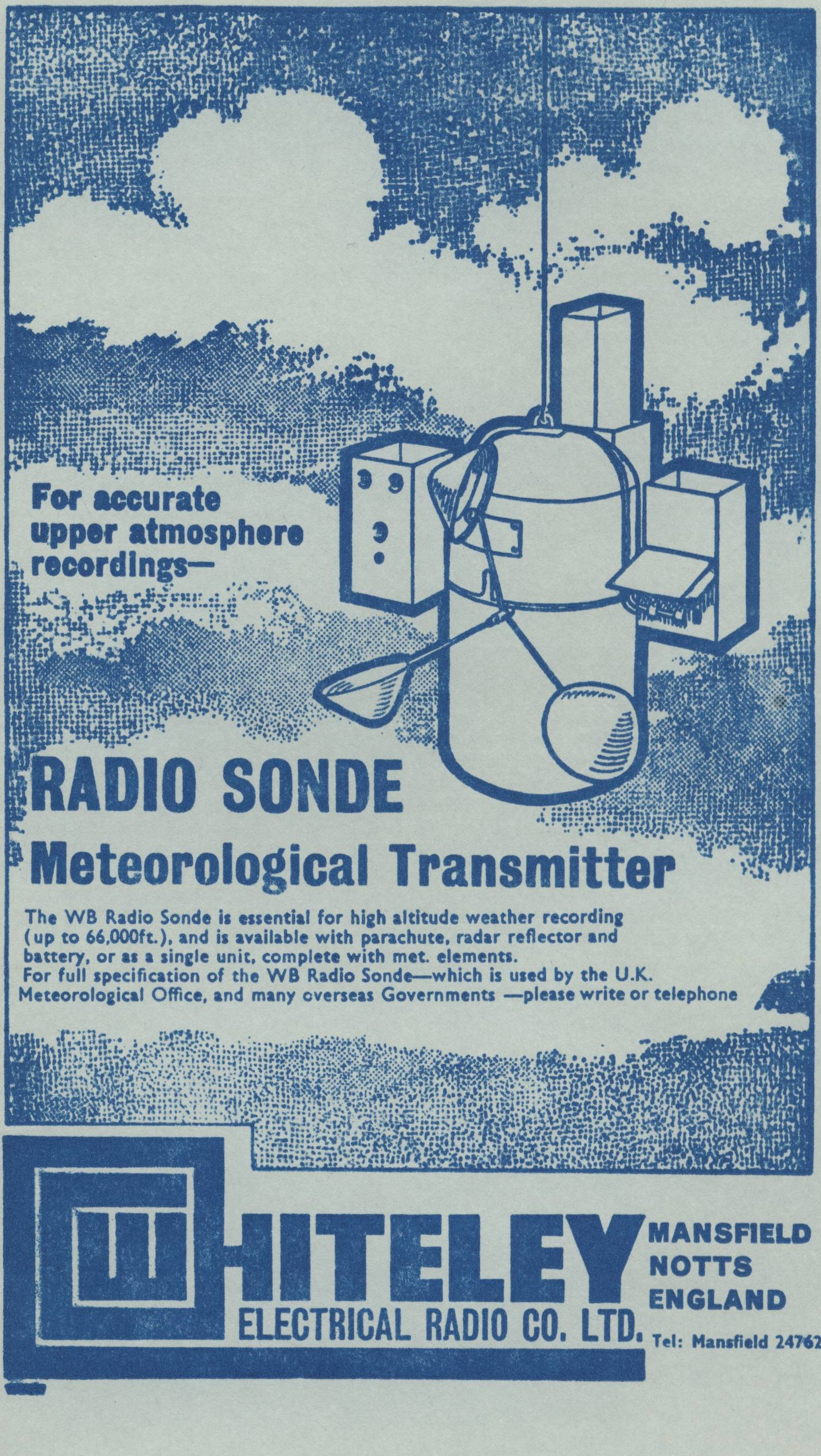
'The Water Resources Act 1963 is based on a principle which is fundamental to the proper management of water resources: that one authority should be responsible for all the water resources in a catchment, whether the water is on the surface or in the ground, and for all aspects of managing those resources . . . Experience over the past five years, however, has shown that the Act did not take this principle far enough . . . The national water authority should be as comprehensive in its responsibilities as river authorities are . . . The technical staff of the river basin authorities must be strengthened to match their additional responsibilities . . . If our premises are sound . . . then the organization for achieving what will be needed must be established without delay. A major revision of the Water Resources Act 1963 could hardly become law in less than two years from now with another two years thereafter to appoint the new authorities and for them to get into business, say in 1975. If this were only an interim stage, it would be at least 1980 before there could be any possibility of proceeding to the second and final stage which could not then come into operation until the mid 1980s at the very earliest. *That would be too late.*' (Reviewer's italics; five words amongst the most important in the report.) ' . . . We await with keen interest the report of the Central Advisory Water Committee.'

Since the above review was written the Central Advisory Water Committee report has appeared and, against the firmness of the Water Resources Board annual report, is something of an anticlimax. With so much at stake in terms of the future health and amenities, economy and prosperity of our community, the next step on the road to a new Act is now awaited with keen interest — the Government White Paper.

A. BLEASDALE

AWARD

We note with pleasure that the sixteenth International Meteorological Organization Prize for outstanding work in meteorology and international collaboration has been awarded for this year to Dr J. G. Charney, Professor of Meteorology at the Massachusetts Institute of Technology, Cambridge, U.S.A., by the Executive Committee of the World Meteorological Organization.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