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RAINFALL ON INDIAN OCEAN CORAL ISLANDS

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1. INTRODUCTION

The existence of steep rainfall gradients in the tropical Pacific is well documented, and many workers have drawn attention to the effects of rainfall variations on island ecologies, particularly in the Gilbert and Marshall Islands. Rainfall gradients also exist in the Indian Ocean, but fewer records are available for islands in this area, and the spatial patterns of rainfall distribution and variability are still only approximately known.

As part of a programme of work on coral islands and reefs in the Indian Ocean, particularly in the western and central sectors, an attempt has been made to assemble rainfall data from as many coral island stations as possible in order to demonstrate the extent of spatial and temporal variability. This paper summarizes these records, and the data are used as the basis of a series of maps of the Indian Ocean showing the distribution of annual, seasonal and monthly rainfalls. Because the paper is concerned only with the establishment of rainfall patterns, no attempt is made to relate these patterns to climatological causal factors.

Studies of rainfall over the oceans and on oceanic islands are subject to peculiar difficulties. Stations are generally few in number and far apart, and, in the Indian Ocean, are markedly clustered in the western sector. The longest, most continuous, and most reliable records are usually those from high islands, such as the Mascarenes and the Comoros, where, however, orographic and other local effects lead to rainfalls unrepresentative of the surrounding ocean area. An extreme example is given by Réunion, in the Mascarenes, where relief effects

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combined with a tropical cyclonic disturbance to give a world record rainfall intensity of 187 cm over 24 hr in 1952 (Paulhus 1965). In contrast, coral island records are, with some exceptions, brief, often incomplete, and in some cases maintained by untrained and unsupervised observers.

Records are presented in this paper for 21 Indian Ocean coral island stations. These are listed, with period of record, mean annual rainfall over this period, and variability, in Table 1. The standard deviation of annual rainfalls is calculated for those stations with a period of record greater than ten years, and variability is given by $100\ \sigma/\bar{X}$. The data used are derived from a variety of sources. Records for Cargados Carajos, Agalega, Salomon, Peros Banhos and Diego Garcia are published by the Mauritius Department of Meteorology in the monthly Results of *Magnetical and Meteorological Observations from the Royal Alfred* Observatory (up to 1950) and in the monthly Meteorological Observations and Climatological Summaries (1951-). Records for Amini Divi, Androth and Agathi, in the Laccadive Islands, while not included in Monthly rainfall of India, have been made available by the Meteorological Department, Government of India, at Poona. The Meteorological Department, Bracknell, England, has provided published and unpublished records for Christmas Island, Cocos Keeling, Minicoy and Tromelin. Many shorter records have been abstracted during visits to Indian Ocean islands, mostly from records in the Department of Meteorology, Mahé, Seychelles (Aldabra, Alphonse, Bird, Darros, Denis and Poivre). Figures for Addu Atoll were obtained from the Royal Air Force, Gan, and for Assumption from the island Manager. Figures for Malé have been published by Wells (1948).

2. SPATIAL DISTRIBUTION OF ANNUAL RAINFALL

The first serious attempt to map the distribution of rainfall over the oceans was that of Supan (1898), but because of lack of data most of the Indian Ocean was left blank in his map. Indian Ocean data were first assembled by Schott (1933, 1935, pl. 19) and Meinardus (1934), and their maps are given in Figures 1A and 1B. These both show an equatorial belt of high rainfall (greater than 2000 mm per annum) extending from east to west across the ocean almost to the Seychelles, with totals greater than 3000 mm in the easternmost area. Broadly similar maps have been published by The Times Atlas of the World (Bartholomew, editor, 1958: Figure 1C) and by the Russian Norskoi Atlas (Drozdov 1953) and the Fiziko-Geograficheskiy Atlas Mira (Kuznetsova and Sharova 1964: Figure 1D). These later maps show the area enclosed by the 2000 mm isohyet to be rather more extensive, including the Seychelles and Amirantes, and in the case of the Russian map the Aldabra group as well. These maps are based mainly on records from high island stations (Rodriguez, Réunion, Mauritius, Mahé, Socotra, and stations in the Andamans and Nicobars). Only four coral island stations are used, all with long periods of record: these are Minikoi, Diego Garcia,

Cocos-Keeling and Christmas Island (the latter an elevated reef island rising to a maximum elevation of 360 m). Records from the high islands certainly exaggerate oceanic rainfalls, and arbitrary reduction factors are used when drawing isohyets for the open ocean. In addition, large areas of the Indian Ocean lack any island records at all, and isohyets are interpolated based on general considerations of atmospheric circulation and pressure distribution. These problems are discussed by Wust (1950) and Jacobs (1968).

Figure 2 plots mean annual rainfall totals for all the coral islands for which data are available. As noted in Table 1, these records vary widely in length and continuity. A distinction is therefore made in Figure 2 between stations with more and those with less than 10 years of record. Because of the variability of coral island rainfalls short period records are generally of little value in deriving mean values for isohyet plotting: compare, for example, the length of record and mean annual rainfall for three stations in the Amirantes (Alphonse, 14 yr, 1930 mm; Darros 12 yr, 1497 mm; Poivre, 2 yr, 2045 mm). Figure 2 is thus based primarily on the values for stations with records longer than 10 years. Mean values for some high island stations in the Seychelles and the Mascarenes are also shown, but these were not used in drawing the isohyets.

Coral islands give a better indication of open-ocean rainfall than high islands, because their small size and lack of height lead to minimal topographic effects. In a detailed study of rainfall incidence at Eniwetok Atoll, Marshall Islands, for example, Lavoie (1963) concluded that the atoll itself has a negligible effect on rainfall amounts and incidence. It is reasonable to conclude, therefore, that the isohyets drawn from coral island records in Figure 2 define a map of the distribution of rainfall over the ocean.

The general pattern shown in Figure 2 resembles those in Figure 1, with two important differences: (a) Figure 2 shows the existence in the central Indian Ocean of rainfalls in excess of 3000 mm, rather than the 2000 mm of the earlier maps, with maxima of more than 3700 mm in the northern Chagos atolls of Peros Banhos and Salomon; and (b) Figure 2 also shows the existence in the southwest Indian Ocean, north of Madagascar, of an area with less than 1000 mm per annum (about 800 mm on Aldabra and Assumption). Rainfall in the Amirantes is also lower in Figure 2 than in Figure 1. Gradients in rainfall over the Indian Ocean are thus considerably steeper than suggested by previously published maps: the most striking gradient is that from the Chagos Archipelago northwards to the Laccadives along an almost continuous chain of atolls, though lower annual totals are found along the gradients from the Chagos across the western Indian Ocean to the Aldabra group.

It is interesting to compare the mean annual rainfalls of Indian with Pacific Ocean atolls. Table 3 lists some Pacific atolls which may be compared with coral islands in the Indian Ocean in terms of mean annual rainfall.

3. SEASONAL RAINFALL DISTRIBUTION

Maps of the seasonal distribution of rainfall over the oceans have been prepared by Möller (1951) and Jacobs (1968). Figure 3 shows the distribution of mean rainfall for the three-monthly periods December-February, March-May, June-August, and September-November according to Möller. These show a seasonal maximum in the central Indian Ocean (Chagos Archipelago) in December-February, and in the Maldives during the southwest monsoon of June-November. The influence of the monsoonal system in the northern Indian Ocean leads to a change in direction of the isohyets from east-west to north-south during the northern summer. Möller's maps are based mainly on high island records.

Plotting coral island data for the same seasons gives the distributions shown in Figure 4. The patterns are similar to Möller's but the magnitudes are considerably different. In each season Möller underestimates the amount of rainfall in the central area, and also the westward extent of the high rainfall belt. Discrepancies between Möller's values and those in Figure 4 are greatest in the Chagos archipelago and least in the Aldabra group.

4. MONTHLY RAINFALL DISTRIBUTION

Maps of the spatial distribution of mean monthly rainfall have been published by Albrecht (1951), mainly from high island data. Figures 5 and 6 show isohyets for each month of the year for coral island stations. All stations were plotted, but the isohyets are mainly based on stations with records longer than 10 years. Mean monthly figures for all the reef island stations are given in Table 2.

The monthly maps clearly show the concentration of rainfall in the central equatorial belt during January, February, March and April; the increasing rainfall associated with the Indian summer monsoon extending northwards through the Maldives during May; the reversal of the latitudinal rainfall gradient during the monsoon proper, in June, July and August, with highest rainfall in the Laccadives, decreasing southwards; and finally the retreat of the monsoon and re-establishment of the equatorial maximum in September, October, November and December. In the southwest Indian Ocean, highest monthly rainfalls occur in November and December (about 50 mm), January (100 mm), February (150 mm), March (100 mm) and April 150 mm). There is a similar monthly pattern in the eastern Indian Ocean, at Cocos-Keeling and Christmas Island, though totals are higher.

5. INDIVIDUAL STATIONS

Data for individual stations with longer periods of record are presented in the form of scatter diagrams, showing actual rainfall for each month of record and the arithmetic mean over the period of record, in Figures 7-11. Mean annual and mean monthly totals for these stations are given in Tables 1 and 2. The actual monthly figures for these stations and for those with only a short period of record are available on request. The stations are grouped geographically, and brief observations may be made on each group.

In the Maldives and Laccadives, good records are available for Addu, Minicoy and Amini Divi (Figure 7), spanning a north-south distance of 1300 km. At Addu the rainfall is dominated by the migration north and south of equatorial shear zones and no monsoonal influence is apparent (Stoddart, editor, 1966). At Minicoy and Amini Divi, however, annual totals are higher and there is a pronounced seasonal maximum in May-December and minimum in January-April. The monsoon is apparent earlier at Minicoy than at Amini Divi. As annual totals increase, so does variability, from 13 to 23%.

In the Chagos to the south (Figure 8), with the highest annual totals of all Indian Ocean atolls, rainfall distribution is approximately bimodal, with peaks in January-February and October. Variability is high, especially on Salomon (23%) and Peros Banhos (30%), but these are the only Indian Ocean atolls where completely dry months do not occur. Very high monthly totals are frequently recorded, with a maximum of 1037 mm in June 1952--the second highest monthly total recorded on an Indian Ocean coral island (the highest being 2208 mm in January 1965 at Cocos-Keeling Atoll).

Figure 9 shows trade-wind stations in the central Indian Ocean, and Figure 10 similar stations in the western Indian Ocean. All show an alternation between a dry period during the Southeast Trades, roughly May-November, and a rainy season during the calms of northwesterlies of December-April. Variability is greatest during the wettest months and least during the Trades, when a proportion of months, particularly in the western Indian Ocean, are completely dry.

Rainfall records are available for only two eastern Indian Ocean coral islands, Cocos-Keeling and Christmas Islands. Both show a maximum during the early part of the year and a pronounced minimum during September and October. Variability is higher at Christmas Island, where the record is however much longer.

No analysis is undertaken in the present paper of patterns in the temporal variation of rainfall. However, it can be stated that there is good correlation in the occurrence of wet and dry years in particular geographic areas. Thus the three Chagos atolls of Diego Garcia, Peros Banhos and Salomon, together with Addu Atoll in the

Maldives, show very similar temporal patterns; as do islands in the Seychelles area (for example Darros and Denis) and, to a lesser extent, Minicoy and Amini Divi.

ACKNOWLEDGEMENTS

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TABLE 1.
INDIAN OCEAN RAINFALL STATIONS, WITH DETAILS OF LENGTH OF RECORD, MEAN ANNUAL RAINFALL, AND VARIABILITY

Station	Latitude	Longitude	Number of complete years of record	Period of record	Mean annual rainfall mm	σ mm	$100\sigma/\bar{X}$
Addu	0.38 S	73.10 E	9	1957-1967	2382.5	316.1	13.26
Agalega	10.22 S	56.37 E	20	1947-1966	1688.4	310.2	18.37
Agathi	10.59 N	72.14 E	3	1965-1968	1225.1	-	-
Aldabra	9.26 S	46.25 E	5	1949-1953, 1958-1959, 1967-1970	760.1	-	-
Alphonse	7.05 S	52.50 E	14	1949-1962	1350.0	256.1	18.97
Amini Divi	11.30 N	72.58 E	60	1901-1953, 1955-1963, 1965-1968	1515.9	348.6	23.23
Androth	10.51 N	73.41 E	1	1965-1968	2022.3	-	-
Assumption	9.45 S	46.30 E	2	1964-1967	867	-	-
Bird	3.41 S	55.06 E	2	1961-1962	1973.3	-	-
Cargados	16.27 S	59.36 E	20	1947-1966	973.6	272.0	27.93
Christmas	10.30 S	105.40 E	48	1901-1941, 1947-1952, 1965-1967	2037.8	578.5	23.38
Cocos-Keeling	12.00 S	96.50 E	15	1952-1968	2006.5	724.9	36.12
Darros	5.45 S	53.40 E	12	1950-1962	1496.7	393.8	26.31
Denis	3.47 S	55.39 E	12	1951-1962	1730.0	383.8	22.18
Diego Garcia	6.34 S	72.24 E	18	1937-1938, 1950-1966	2598.9	464.9	17.88
Male	4.00 N	73.28 E	4	c. 1941-1944	2055.9	-	-
Minicoy	8.29 N	73.01 E	65	1891-1895, 1897-1968	1628.1	242.3	14.88
Peros Banhos	5.18 S	72.00 E	14	1950-1966	3998.9	1184.7	29.62
Poivre	5.50 S	53.20 E	2	1961-1962	2045.2	-	-
Salomon	5.16 S	72.25 E	15	1949-1966	3750.7	860.3	22.93
Tromelin	15.51 S	54.25 E	11	1955-1968	1073.3	188.0	17.51

TABLE 2.
MEAN MONTHLY RAINFALLS OF INDIAN OCEAN CORAL ISLANDS (mm)

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Addu	249.3	123.4	93.3	193.7	231.2	219.4	162.7	177.8	151.7	287.9	210.3	247.2
Agalega	252.4	195.9	158.1	156.3	146.9	91.4	99.0	76.1	80.6	118.4	106.2	207.5
Agathi	10.1	0	0.7	5.1	46.2	309.0	296.7	135.9	144.0	78.5	84.6	115.1
Aldabra	93.8	118.5	121.0	164.2	36.8	19.9	20.5	11.7	10.6	5.8	54.8	57.2
Alphonse	246.4	201.7	140.7	143.6	65.5	50.0	35.5	34.3	52.4	80.0	111.5	189.0
Amini Divi	16.8	2.6	3.4	23.8	142.1	374.7	314.3	204.0	149.0	146.0	83.2	38.8
Androth	21.1	0	19.7	29.0	76.7	325.2	415.5	260.6	159.9	128.6	118.2	201.7
Assumption	164	96	126	169	45	31	32	39	6	6	39	95
Bird	290.8	295.6	81.9	127.6	107.1	18.4	29.8	148.6	294.5	123.5	290.7	164.3
Cargados Carajos	167.1	158.0	176.0	11.36	56.9	47.7	56.3	47.1	21.3	24.0	29.2	76.4
Christmas	221.3	284.9	271.3	226.0	201.8	149.6	107.0	55.7	48.9	60.2	173.6	193.3
Cocos-Keeling	325.9	136.4	225.8	202.4	171.9	182.2	213.4	151.8	61.9	92.0	79.4	170.9
Darros	254.2	186.0	151.2	134.4	124.4	48.6	34.3	40.4	68.3	122.2	104.5	226.9
Denis	297.4	175.5	142.3	102.3	109.1	104.2	35.2	103.3	126.4	140.6	134.2	248.9
Diego Gracia	297.1	264.7	201.8	194.0	172.6	153.2	149.3	166.0	190.0	260.9	198.6	221.8
Malé	220.7	7.1	89.2	110.5	185.8	178.2	155.1	135.4	125.8	357.2	129.5	361.4
Minicoy	45.0	24.2	21.1	60.1	184.1	293.7	228.8	196.5	163.6	190.2	137.5	89.1
Peros Banhos	387.5	407.6	296.1	300.7	238.6	160.5	314.3	266.8	321.9	402.1	351.4	371.9
Poivre	397.6	245.2	147.8	189.7	52.4	95.2	43.1	57.5	222.8	189.4	172.8	231.1
Salomon	431.7	384.9	255.5	250.0	282.0	160.6	339.4	241.7	356.4	421.7	292.1	291.5
Tromelin	199.6	136.6	191.7	109.3	61.9	55.6	81.3	60.2	32.2	34.1	42.4	107.6

TABLE 3.

MEAN ANNUAL RAINFALLS OF INDIAN AND PACIFIC OCEAN ATOLLS (mm).
PACIFIC OCEAN DATA FROM WIENS (1962)

Indian Ocean		Pacific Ocean	
Peros Banhos	3999	Jaluit	3988
Salomon	3751	Palmyra	3810
		Funafuti	3378
		Washington	3099
		Majuro	3048
Diego Garcia	2599	Lamotrek	2641
Addu	2382	Manihiki	2413
		Palmerston	2108
Malé	2056	Fanning	2057
Poivre	2045	Nauru	2057
Christmas	2038		
Androth	2022		
Cocos-Keeling	2006	Niue	2007
Bird	1937	Ujelang	1956
Denis	1930	Ocean	1930
		Mopelia	1854
Agalega	1688		
Minicoy	1628	Tarawa	1626
Amini Divi	1516		
Darros	1497	Rangiroa	1473
		Christmas	1473
Alphonse	1350	Eniwetok	1346
Agathi	1225		
		Onotoa	1168
		Raroia	1168
Tromelin	1073		
Cargados Carajos	974		
Assumption	867	Hull	838
Aldabra	760	Malden	711
		Wake	610
		Canton	432

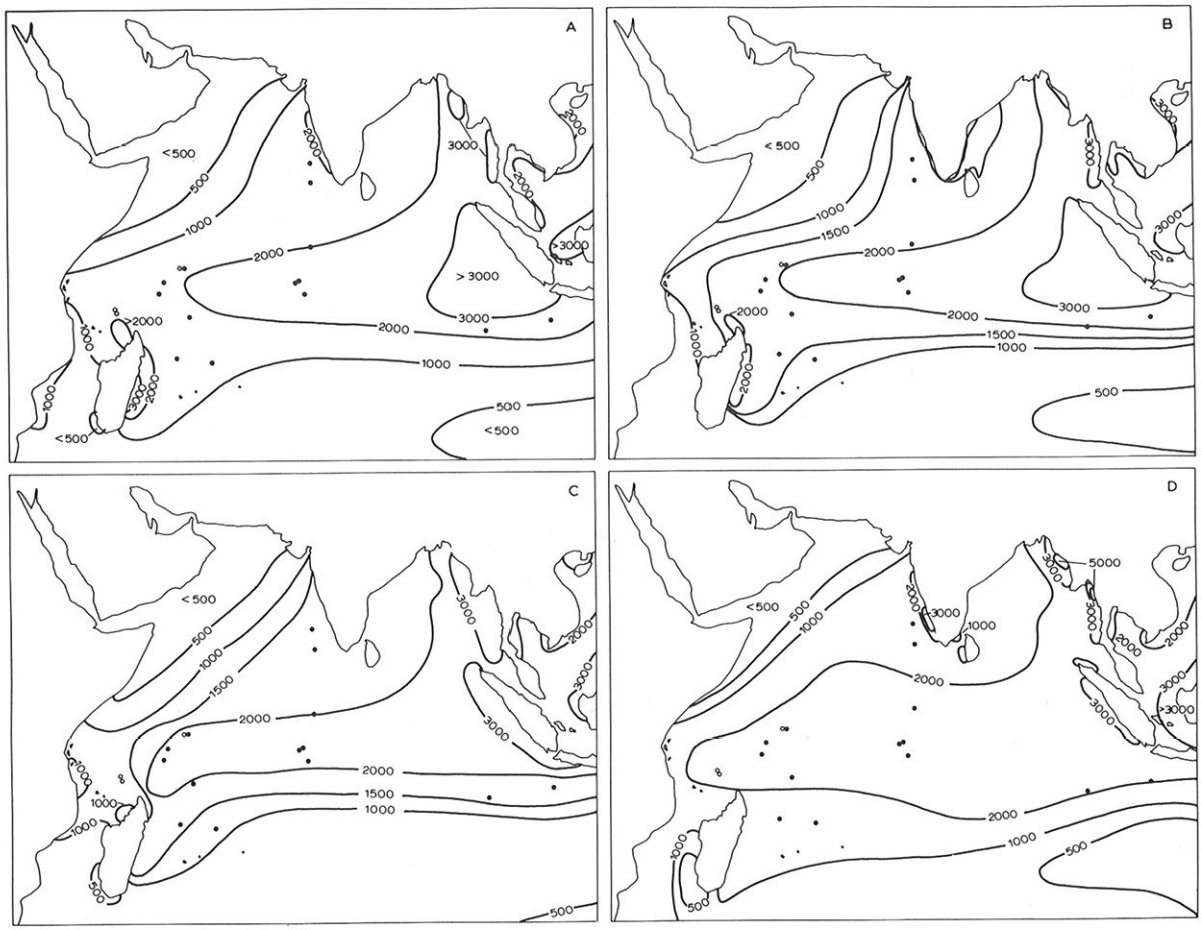

Fig. 1. Distribution of mean annual rainfall over the Indian Ocean (mm). A: Meinardus (1934). B: Schott (1933, 1935). C: Bartholomew (1958). D: Kuznetsova and Sharova (1964). The stations shown are those used in this paper and not those on which these authors based their maps.

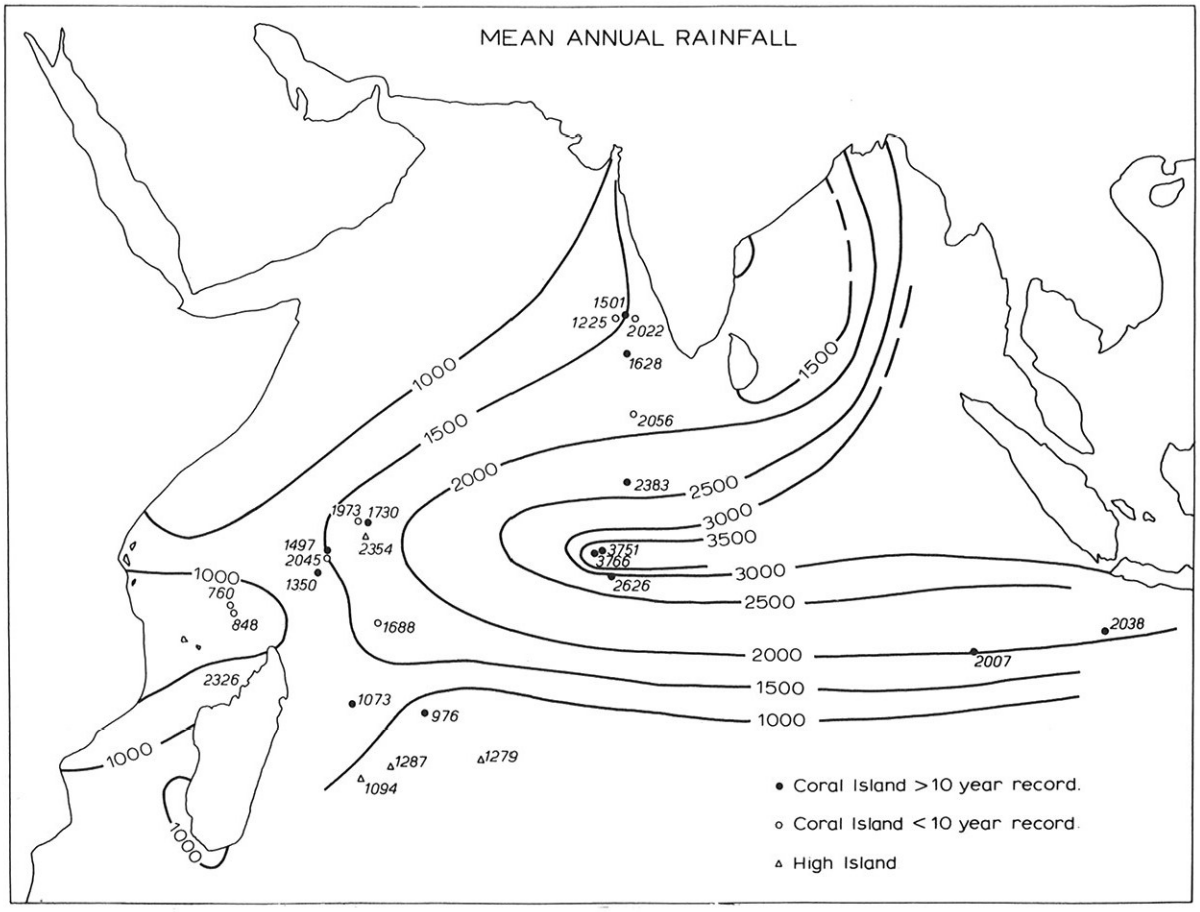

Fig. 2. Distribution of mean annual rainfall over the Indian Ocean (mm), with isohyets based on coral island stations with records longer than 10 years.

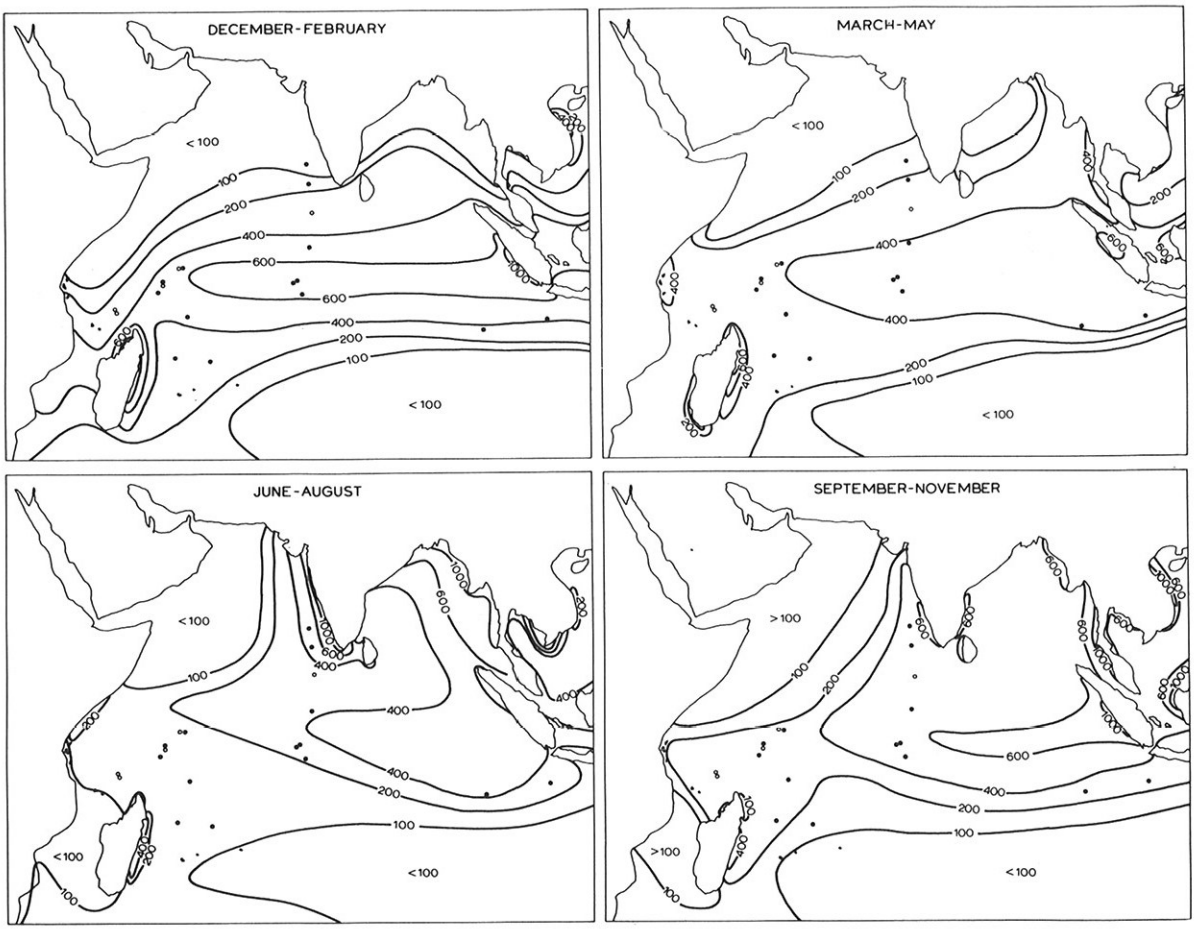

Fig. 3. Seasonal distribution of rainfall over the Indian Ocean (mm), after Möller (1951). The stations shown are those used in this paper and not those used by Möller.

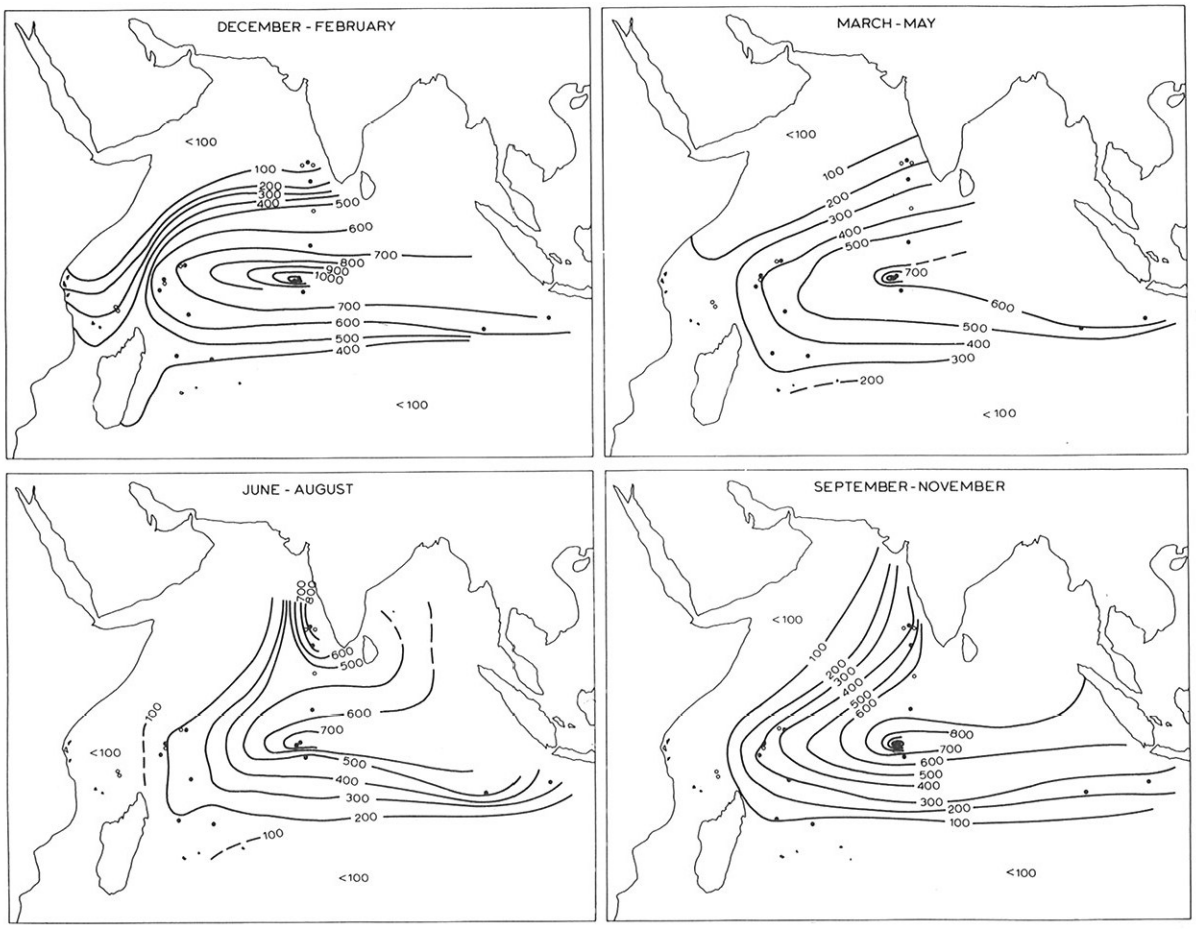

Fig. 4. Seasonal distribution of rainfall over the Indian Ocean (mm), based on coral island stations. Open circles: stations with records shorter than 10 years; dots, records longer than 10 years.

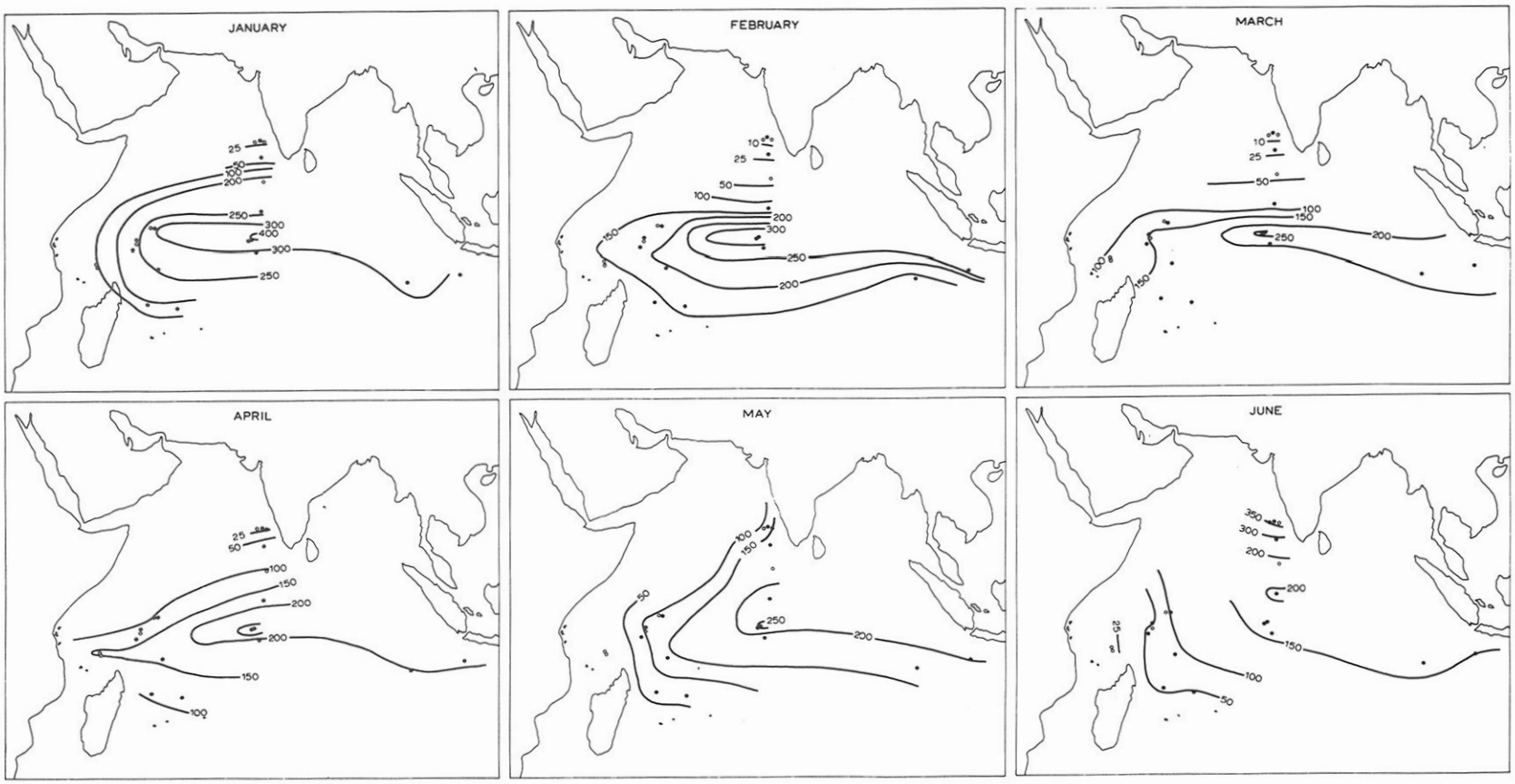

Fig. 5. Distribution of mean monthly rainfall over the Indian Ocean (mm), January-June, based on coral island data. Open circles: stations with records shorter than 10 years; dots, records longer than 10 years.

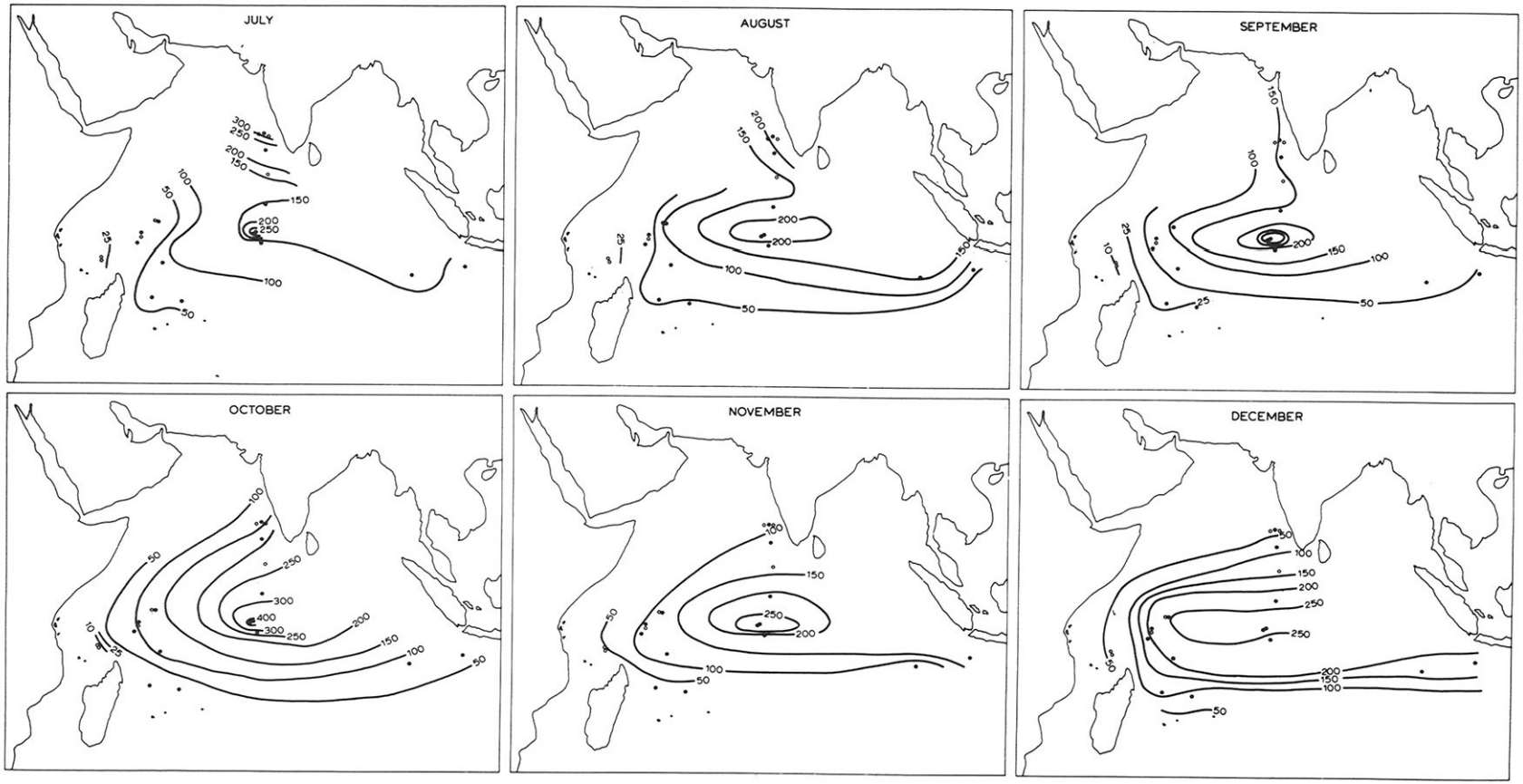

Fig. 6. Distribution of mean monthly rainfall over the Indian Ocean (mm), July-December. Conventions as for Figure 5.

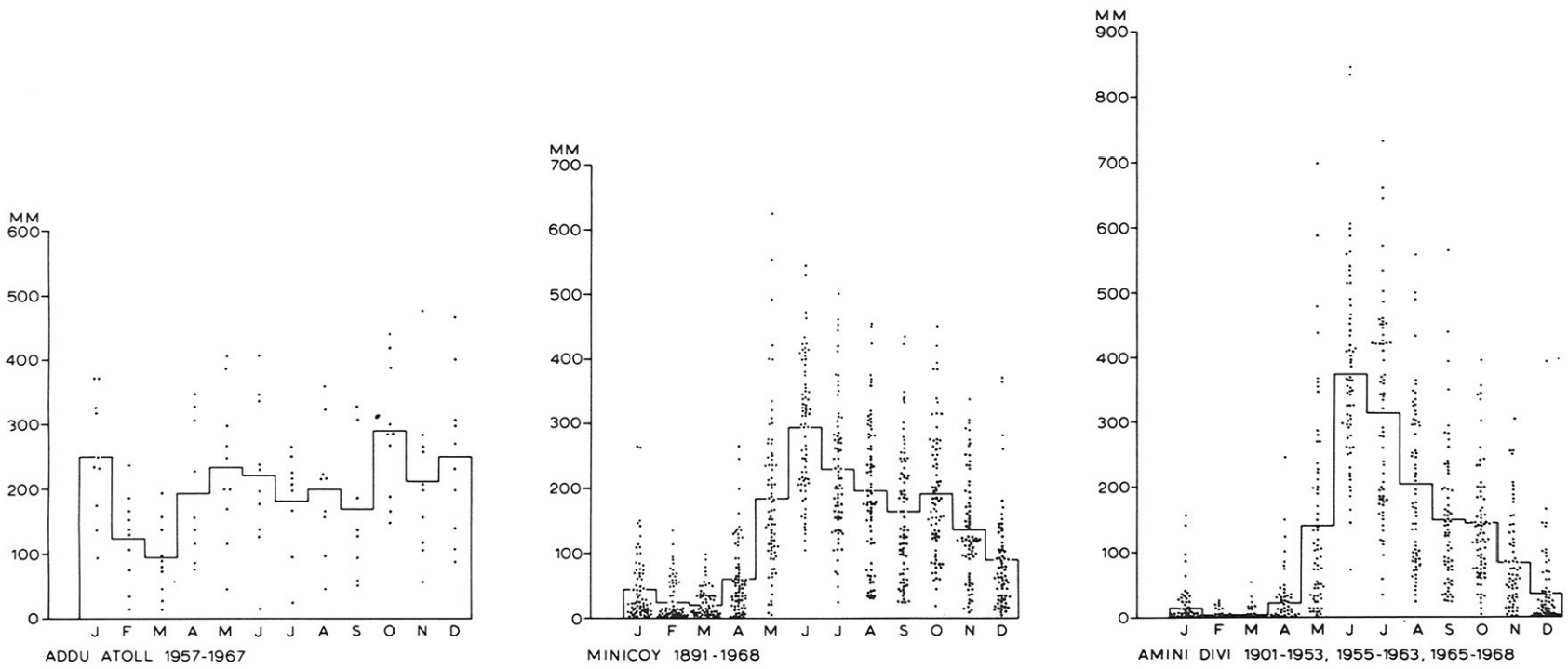

Fig. 7. Mean monthly rainfall and actual monthly totals over the period of record for Addu Atoll, Minicoy and Amini Divi.

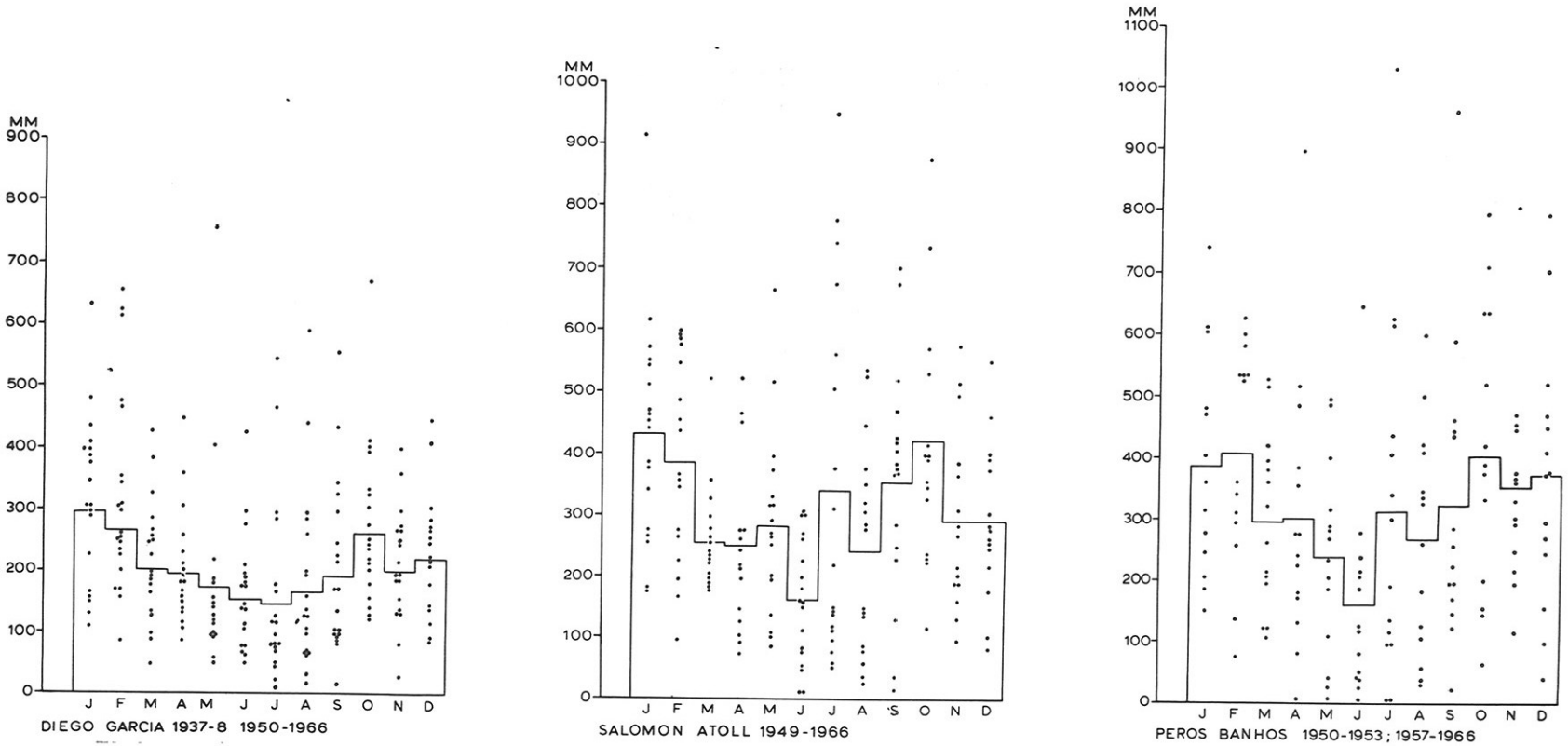

Fig. 8. Mean monthly rainfall and actual monthly totals over the period of record for Diego Gracia, Salomon and Peros Banhos Atolls, Chagos Archipelago.

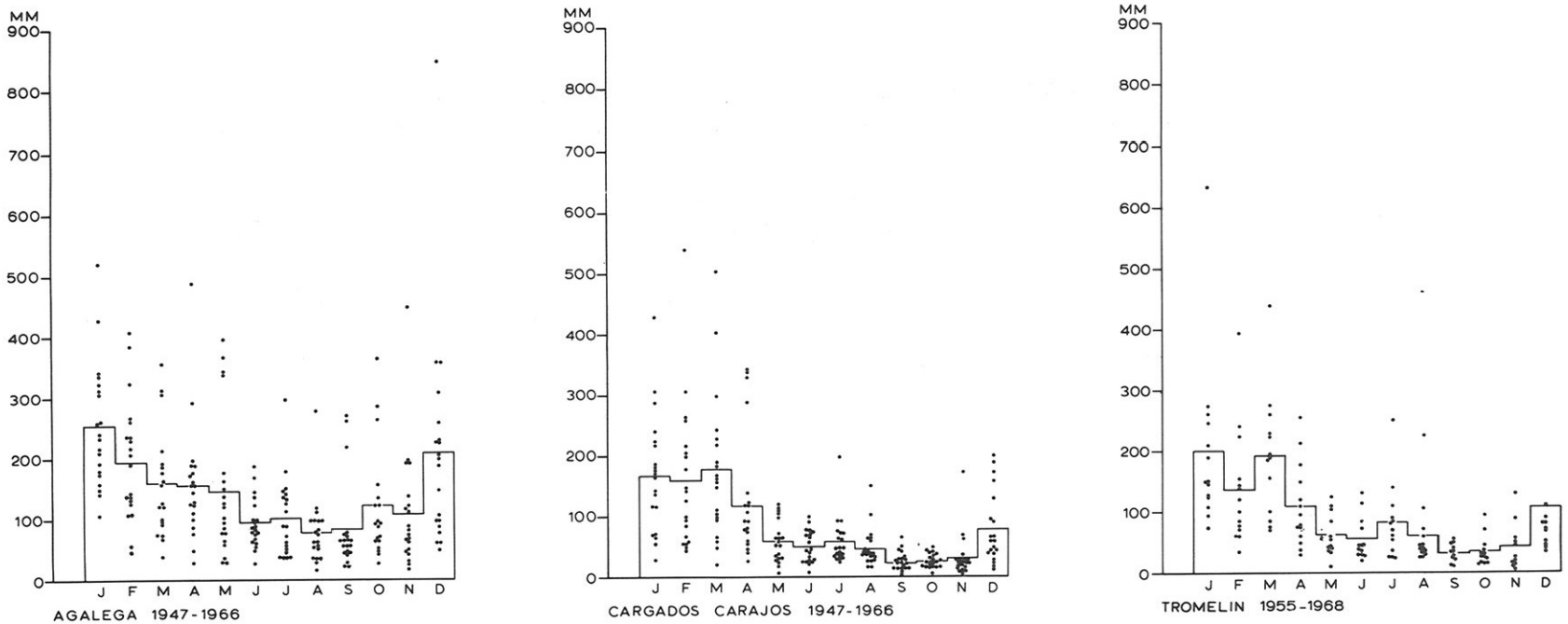

Fig. 9. Mean monthly rainfall and actual monthly totals over the period of record for Agalega, Cargados Carajos and Tromelin.

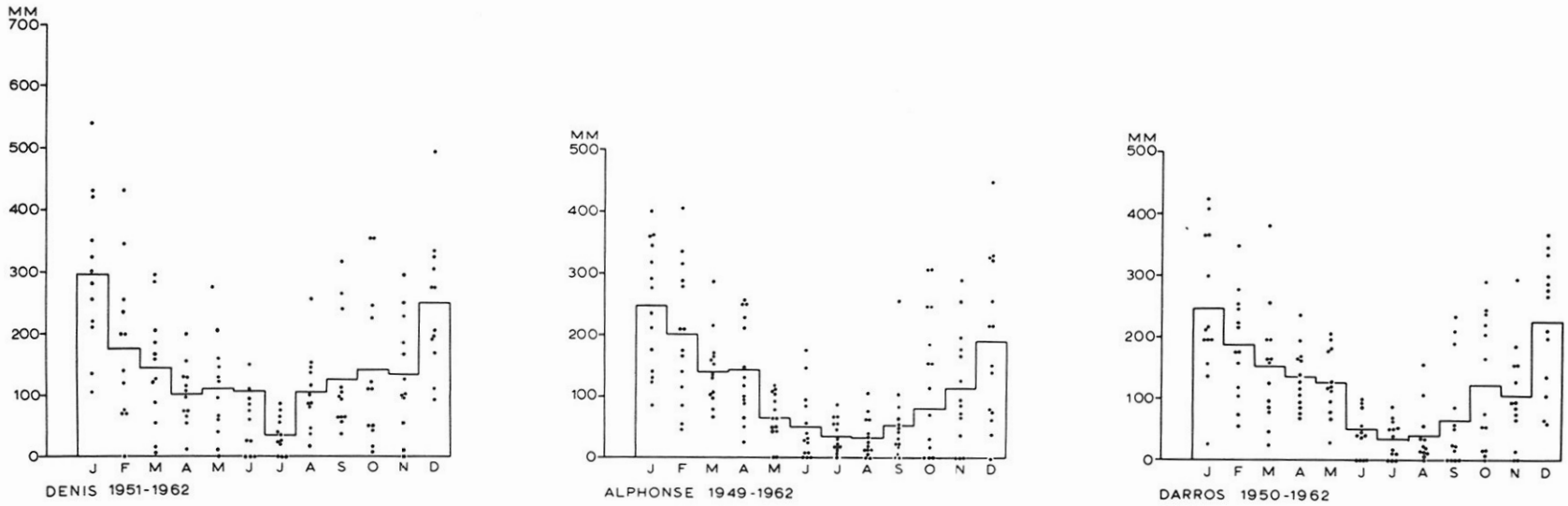

Fig. 10. Mean monthly rainfall and actual monthly totals over the period of record for Dennis, Alphonse and Darros.

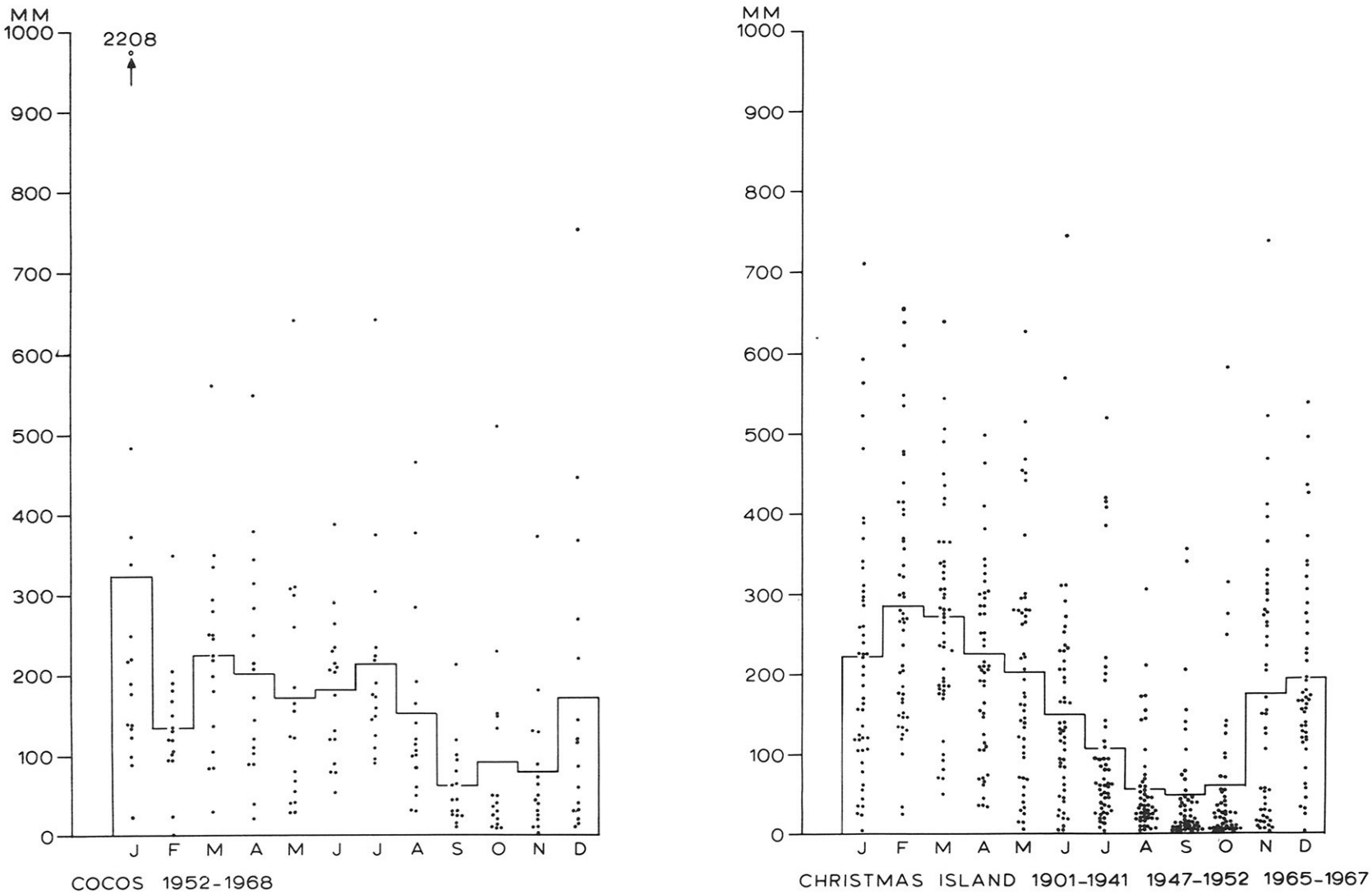

Fig. 11. Mean monthly rainfall and actual monthly totals over the period of record for Cocos-Keeling and Christmas Islands.