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Temporal and spatial variations in precipitation on Aldabra

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Analysis of hourly rainfall data from Aldabra has indicated that the atoll influences its own weather as recorded at the Research Station on Ile Picard. The strength of this local influence varies with the season and may be related to the relative temperature difference between lagoon surface water and the atmosphere above it. The direction and strength of the prevailing wind may also be of some importance. The rôle of the semi-diurnal atmospheric pressure waves is not clearly evident at all times but is most prominent during the early hours of both wet and dry seasons. Its effect may also be present in the slight increase in rain frequency during the late afternoon of the trade wind seasons.

The trans-atoll variations in rainfall amounts confirm the earlier reports of non-synchronous rainfalls. There is some indication of seasonal variation of rainfall at different points around the atoll relative to that received at the Research Station. The northwest and southwest parts of the atoll may receive more rain than the northeast or west central parts.

The study of precipitation on small oceanic islands has attracted attention for some time. Wiens (1962) collated reports from Pacific islands which suggested that atolls were too low to produce orographic rain and too small to affect the time of rainfall, but that maximum falls occurred at the time of maximum atmospheric instability: early morning and afternoon. A contrary opinion was expressed by Riehl (1954) who stated that even small islands affected their local weather. The controversy continued when Lavoie (1963) studied nearly 9 years of precipitation records from the atoll of Eniwetok and concluded that that atoll exerted no detectable influence on the meteorological records obtained there. Kiser, Carpenter & Brier (1963) and Brier & Simpson (1969) extended the studies of island precipitation in another direction by looking for causes for the observed diurnal patterns in rainfall recorded from island stations.

The systematic recording of meteorological phenomena from Aldabra began relatively recently and the synopsis of the first year of detailed records is to be found in Farrow (1971), with subsequent longer term summaries by Stoddart & Mole (1977). The regional setting of precipitation patterns for Aldabra was established by Stoddart (1971) and modified by Stoddart & Mole (1977).

This paper analyses nearly 7 years of hourly rainfall records from Aldabra with the view to describing small scale patterns and to seeing whether they relate to features of Aldabra. It also examines rainfall records from several points around the atoll to see if any pattern is evident in the spatial distribution of rainfall.

Diurnal variations

Data and Methods

The data for diurnal rainfall came from 6 years and 11 months of strip chart records (January 1968 to December 1974, excluding March 1968 for which there were no records) made on a

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British Meteorological Office Dines Tilting Siphon recording rain gauge. The gauge was situated on Ile Picard on the west coast of the atoll. At first it was at Settlement at a site moderately protected by tall *Casuarina* and *Cocos* trees (Farrow 1971) but in 1970 it was moved to a less sheltered site at the new Research Station about 1 km south of Settlement (Stoddart & Mole 1977).

Initial processing of the data was done at the Department of Nuclear Physics, Oxford University, by using a special, computer-assisted, semi-automatic system for digitizing rainfall charts of the British Meteorological Office. The resulting monthly summaries consisted of hourly totals of rainfall for each day, the monthly totals for each hour, and the total for the whole month. The few records which proved difficult to analyse by computer were visually checked and either manually analysed or rejected if unanalysable. In total, 2490 records out of a possible 2557 (i.e. 97.4%) were available and acceptable for analysis.

The data were analysed for monthly amounts and frequency of rainfall without regard to hour of occurrence (figure 1), and then for hourly amounts and frequency without regard for month (figures 2 and 3, respectively). Because of the pronounced seasonality in precipitation on Aldabra, the data were separately analysed for trade wind (May–October) and monsoon (November–April) seasons (figures 2 and 3), using the season definition of Farrow (1971) to allow direct comparisons with his results.

Two further reductions of the data, which each simultaneously took account of hourly and monthly variations, resulted in the summary of diurnal patterns of rainfall amount (figure 4) and rainfall frequency (figure 5). The isopleths in these latter two figures mark the periods where values were 25% greater or less than the individual monthly means. The centring of the diagrams on December and January followed the practice of Troll (1958) for stations south of the equator.

All analyses were based upon rainfall events defined here as either the amount or the occurrence of rain not less than 0.1 mm during a 1 hour block of time. Thus if two distinct showers occurred within one hour block, they were recorded as a single occurrence and their sum was the amount for that hour. Furthermore, if one shower spanned the division between two consecutive hour blocks then an occurrence was recorded for each hour and the amount falling within each hour contributed to the amount for that hour. The numerically overriding influence of seasonal variation was removed by expressing variation in each hourly mean from its respective monthly mean. All times are expressed as local time which equals G.M.T. plus 3 h.

Results

Variations in monthly rainfall (figure 1) indicated the strong seasonality in precipitation with both frequency and amount reaching a peak during the 'wet season' from about December to April inclusive. These results were consistent with those of Farrow (1971) and Stoddart & Mole (1977).

Diurnal variations in rainfall amount (figure 2), without regard for season, showed a strong tendency for most rain to fall between 10h 00 and about 15h 00 with a relatively minor peak between 23h 00 and midnight. Periods of relatively little rainfall occurred between 07h 00 and 09h 00 and again from 21h 00 to 23h 00. There was a general decrease in rainfall amount from 15h 00 until 23h 00 and also from 05h 00 to 08h 00.

The diurnal variation in frequency of rainfall without regard to season (figure 3) resembled that shown by amount of rainfall, but with a less marked pattern as none of the extremes exceeded 25% of the mean. The period of greatest frequency was between 14h 00 and 15h 00 which was slightly later than the peak in rainfall amount. A weak, broad, secondary maximum occurred in the hours before dawn. Frequency of rainfall was least between 08h 00 and 09h 00, and 20h 00 and 23h 00, somewhat similar to the periods of lowest rainfall amounts.

An indication of the influence of season upon the diurnal pattern of rainfall was included in figures 2 and 3. The monsoon season was defined as the months of November to April while

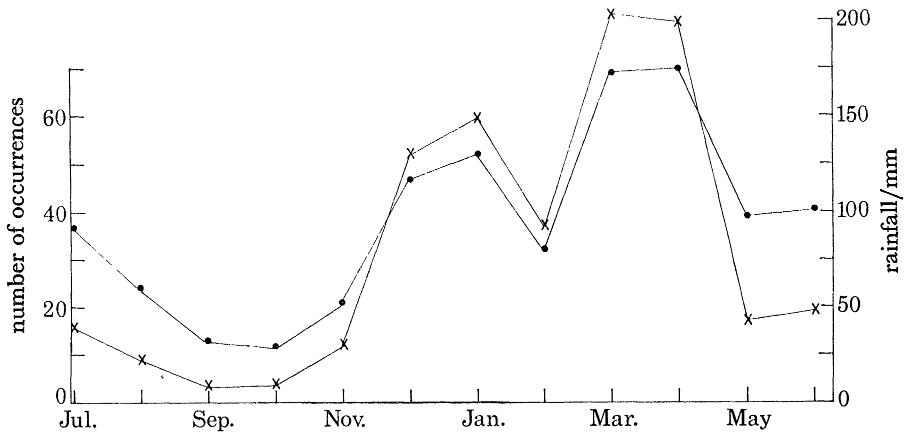

FIGURE 1. Mean monthly amount (×), and frequency (•) of rainfall at the Picard, 1968–74.

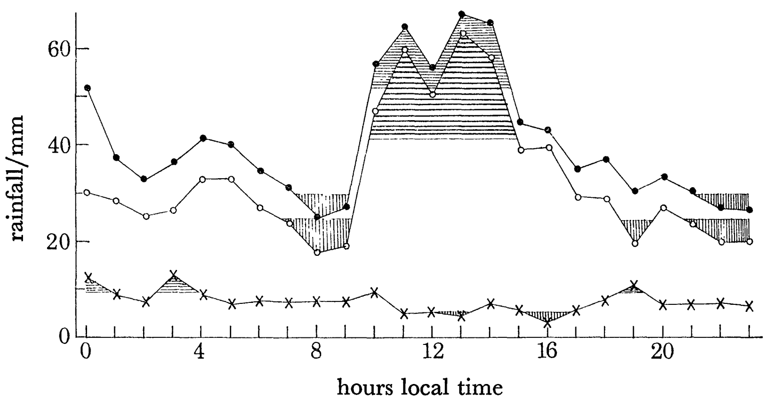

FIGURE 2. Hourly mean amounts of rainfall at the Picard, 1968–74: •, total; o, monsoon season November to April; ×, trade wind season May to October. Horizontal shading represents more than 25% of the mean; vertical shading less than 25%.

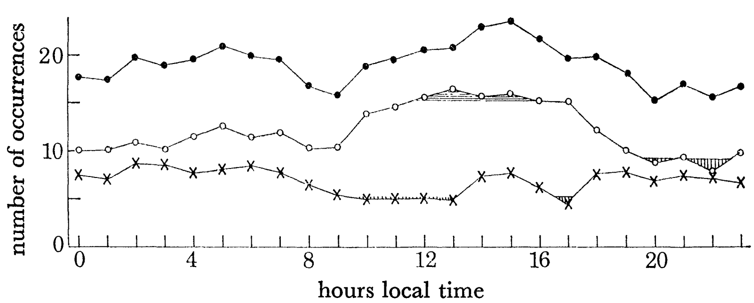

FIGURE 3. Hourly mean number of occurrences of rainfall at the Picard, 1968–74: •, total; o, monsoon season November to April; ×, trade wind season May to October. Shading as in figure 2.

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the trade wind season was May to October. This division followed that of Farrow (1971) in order to make easy comparison with his data. Rainfall amount (figure 2) for the monsoon season closely followed the pattern of the curve for the whole year. Amounts less than 25% of the mean occurred from 07h 00 to 09h 00 and greater than 25% of the mean from 10h 00 to 15h 00. The trade wind season, however, was markedly different. There was no midday peak in rainfall amount during the trade wind season, and there were only small peaks during the early morning and just after sunset. Also at this season there was a tendency for especially low amounts of rain at midday and in the late afternoon.

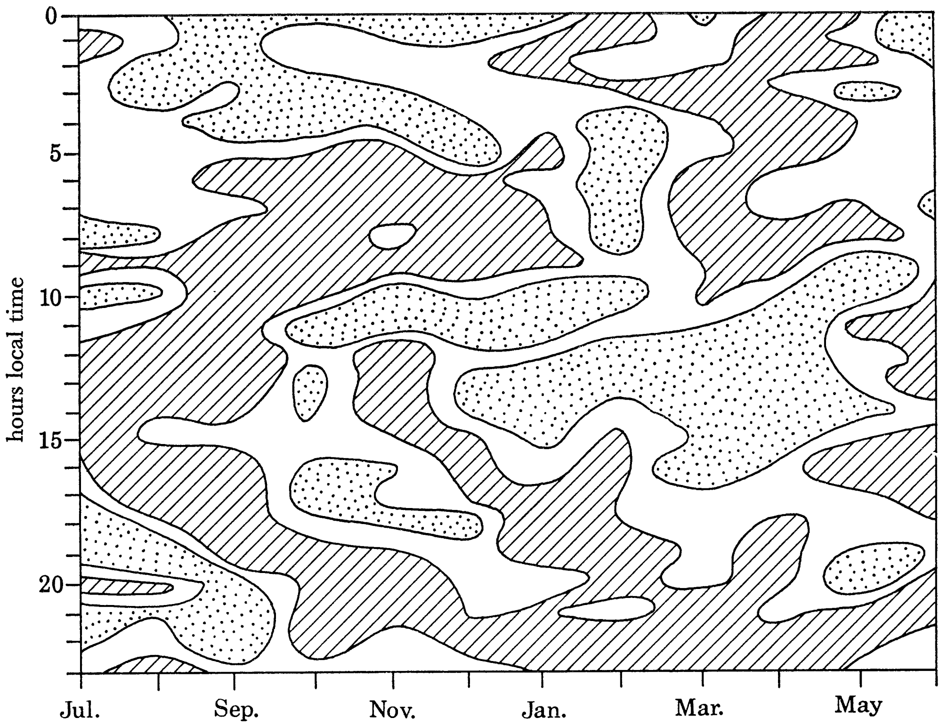

FIGURE 4. Isopleth diagram of rainfall amount at the Picard, 1968–74. Diagonal shading marks time periods that received less than 25% of the appropriate monthly mean rainfall; dotted areas mark the periods receiving greater than 25% of the monthly mean rainfall.

Rainfall frequency during the monsoon season (figure 3) showed a bimodal pattern with greatest frequencies near sunrise and midday to mid-afternoon. These peaks appeared to be slightly later in the day than the corresponding peaks in the amount of rainfall (figure 2). The trade wind frequency curve is subdued with only three minor extremes exceeding ±25% of the mean. There is a maximum at 02h 00–03h 00 and there are minima at 12h 00–13h 00 and near 17h 00.

Figures 4 and 5 provide a further refinement on the relation between diurnal and seasonal patterns of rainfall. There were two major periods of maximum rainfall frequency (figure 5). One was between about midnight and 07h 00 during the months of August–October (November), and the other was from about 09h 00 to 17h 00 during the months of October–April. During November–February there was a midday depression in frequency from about 12h 00 to 15h 00. The period with the least frequency of rain occurred in the morning daylight hours

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during July–November (December). The frequency of rain at other times showed no discernible pattern.

The isopleth diagram of rainfall amount (figure 4) showed extended periods of heavy rainfall during the midday and post-midnight periods similar to the pattern seen for rainfall frequency. There also was an extensive period of dry conditions between the two major peaks in rainfall amount. It appeared that the midday maximum during the wet season was surrounded by a particularly dry period. Such an encircling feature was not prominent in the frequency isopleth. There was a slight development of a post-sunset maximum in both frequency and amount of rain during the trade wind season.

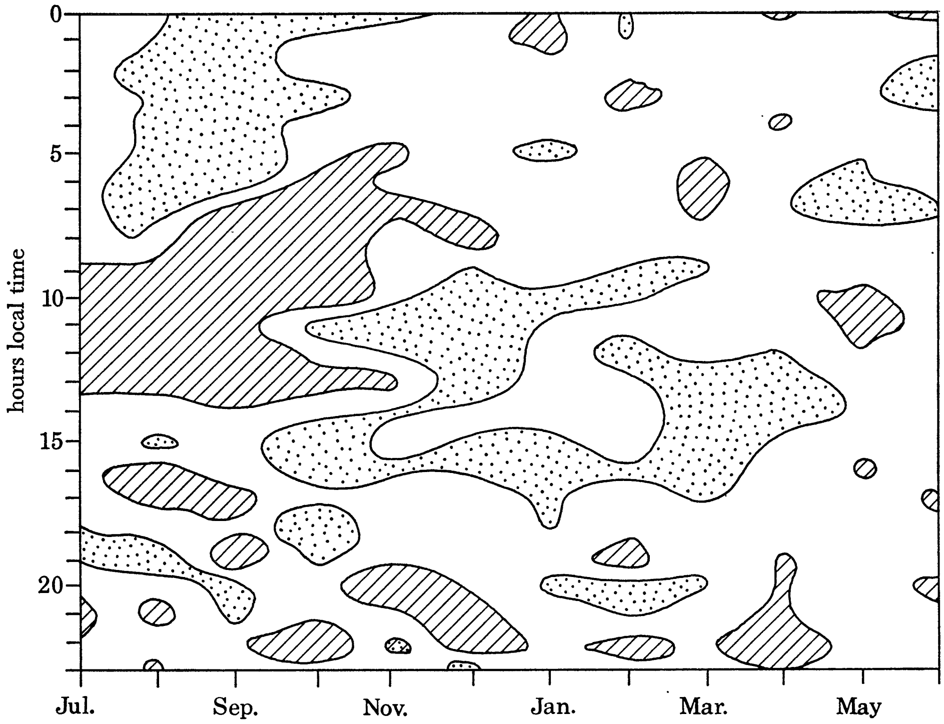

FIGURE 5. Isopleth diagram of rainfall frequency at the Picard, 1968–74. Shading as for figure 4 but with frequency in place of amount.

There were several other differences between the isopleth diagrams for frequency and amount of rainfall. The midday period of rain extended later in the season on the rainfall amount diagram (April), i.e. rainfall frequency appeared to decrease more rapidly than amount as the trade wind season approached. The afternoon 'dry' period was more extensive and continuous on the amount than on the frequency diagram. The post-midnight maximum during the late trade wind season was concentrated on the frequency diagram during August and September between midnight and 07h 00, while on the amount diagram it was spread broadly over August–December and rarely extended later in the day than 05h 00.

The amplitude of the diurnal variation in rainfall was found to be large. On the rainfall frequency diagram it ranged from +135 to −100 % of the monthly mean values while on the amount diagram it ranged from +35 to −100 % of the monthly means.

Discussion

The most prominent feature seen in the pattern of rainfall on Aldabra is the strong influence of season of the year upon both the frequency and amount of rainfall. Rain is both most frequent and most abundant during the monsoon season, which extends from about December to April (figures 1, 4 and 5). The seasonal fluctuations in rainfall correspond to the regular alternation between the southeast trade winds and the equatorial low pressure trough.

The second most prominent feature of rainfall on the atoll is that it exhibits clear diurnal patterns. These patterns are seen to be influenced by season of the year even after bias caused by the numerically larger values of rainfall amount and frequency during the monsoon season compared with the trade wind season have been removed. The diurnal, monsoon, rainfall pattern is dominated by the large midday peak (figures 2–5) which should not be interpreted as indicating the presence of a heated island effect. No similar midday peak is evident in the one year's data presented by Farrow (1971) for Aldabra, indicating that individual years can differ considerably from the mean of several years. A smaller, secondary peak is to be seen during the pre-sunrise hours during both seasons of the year (figures 2 and 3) and may be evidence of the rain inducing effect of the semi-diurnal atmospheric tide described by Brier & Simpson (1969). A close examination is required of both the midday rainfall peak and the possible semi-diurnal atmospheric tide effects.

The daily heating of the atoll's land rim may cause the often observed cloud streets. These appear to result in only restricted falls of rain that are usually out to sea where, in the absence of heating from below, the cloud base is lowered with resultant rain. Malkus, referred to by Farrow (1971), suggested that clouds produced by the heated island effect are less likely to result in precipitation because of the raising of cloud base level also associated with the heating. The lagoon on Aldabra could, by providing both heat and moisture, be the driving force causing the midday monsoon peak in rainfall. Riehl (1954) has shown that transfers of moisture and heat from a water surface to the overlying air occurs only when the water surface temperature exceeds that of the air. Farrow (1971) has demonstrated that lagoon surface temperatures can exceed air screen temperatures during the late trade wind season and predicted as much as 4 °C excess in lagoon temperature over air temperature during the monsoon. The mechanism for causing the midday peak in rainfall, then, could be that the increased moisture supply to the air may result in taller clouds than those produced by the heated island alone. Such taller clouds might then be sufficient to produce precipitation over the atoll. If Aldabra's lagoon is responsible for the midday monsoon peak in rainfall, then the state of the oceanic tide can be expected to be an important factor in modifying its influence. Lagoon waters are expected to be warmest when low tide in the lagoon corresponds with the midday period (i.e. neap tides). Heaviest and most frequent midday falls should be expected at this time also. A detailed study of rainfall pattern in relation to the state of the tide would be rewarding on Aldabra but it would be difficult because of the complex pattern of the flow and ebb of the tide in the shallow lagoon.

The rôle of the semi-diurnal atmospheric tides, which are so prominent a feature of tropical regions, in influencing rainfall has been the subject of some controversy. Lavoie (1963) discounted them as being too weak to cause any rainfall. Brier & Simpson (1969), however, have proposed a mechanism whereby the force of the atmospheric tide, acting upon only limited areas, can be demonstrated to be sufficient to stimulate rain. The hypothesis is that convergence associated with the atmospheric tide will stimulate rainfall near sunrise and sunset. The diurnal rainfall analysis for Aldabra shows a broad, pre-dawn peak in rainfall frequency and amount, but a pre-sunset peak is only scarcely detectable during the trade wind season. The isopleth diagrams (figures 4 and 5) help to resolve the problem by indicating that there is a tendency for the midday peak to extend into the late afternoon peak if the July–September data are merged with the October–December data as was done to produce figures 1 and 2.

It is useful to note here that the demonstration of a relation between hour of rainfall and the semi-diurnal atmospheric tide for Aldabra will not be a simple task. A summary of the monthly mean hour of occurrence of the pressure maxima and minima for September 1973 to October 1974 at the Research Station showed a steady drift in the mean hour of the morning minimum from 06h 42 in September 1973 to 03h 30 in January 1974. During the same time the afternoon minimum shifted from 18h 16 to 16h 06 while the time of the maxima changed virtually not at all. These observations do not show the constancy of phase hour of the atmospheric tide reported by Lavoie (1963) and Brier & Simpson (1969). If the time of occurrence of pressure extremes is always as changeable as noted here it could account for the broadness of the pre-sunrise rainfall peak but could also make difficult the proof on Aldabra of a relation between rainfall and the semi-diurnal atmospheric tide.

One further, final point which may be incidental but is worth noting in relation to rainfall patterns on Aldabra is that the midday peak during the monsoon (figure 4) corresponds roughly to the period of time when monthly mean hourly air screen temperatures (Hnatiuk, unpublished data) equal or exceed 28 °C. Also, the months of greatest rain correspond to the months when open ocean surface temperature equals or exceeds 28 °C (Farrow 1971).

Conclusion

Several factors are acting simultaneously to produce or modify rainfall on Aldabra. Some of these are seasonal factors, local heating of the lagoon and atoll rim, regional storms, ocean tides as they affect lagoon temperature, the force and direction of the prevailing wind, and the semi-diurnal atmospheric tide. At any time one or more of these factors may gain the ascendancy while at another time a different combination may predominate. On average it appears that the seasonal alternation between trade wind and monsoon régimes are most prominent while the heating of the lagoon and the atoll land rim and the semi-diurnal atmospheric tides are next in importance. The other factors act to modify these by either reinforcing or counteracting the tendency to rain, as the case may be.

Trans-atoll variations

Methods

Totalizing rain gauges were established at eight out-stations around the coast of the atoll. They were located at semi-permanent camps which were visited periodically by various workers who could maintain records. For most of the period of recording reported here, it was not practicable to make regular visits to all sites.

The gauges, except one at Passe Houareau which was of standard Meteorological Office construction, each consisted of a plastic 1 gallon (5 l) holding tank, immersed where possible in soil or rocks, connected directly to a plastic receiving cylinder. The holding tank contained a layer of oil sufficient to form a thin layer over water caught and so to reduce, as far as possible, water loss through evaporation.

The locally made gauges were subject to systematic errors. Light showers were unlikely to be adequately recorded through evaporation of the small quantities of water caught on the sides of the warm walls of the gauges. Small water droplets would also tend to remain on the top of the oil and be lost through evaporation. On the few occasions when the oil in the holding tank solidified, exposing an open water surface, some evaporation could have occurred, although the low temperatures at the time and the relatively high humidity would have reduced the rate and quantities involved. All of these factors would act to reduce the measured quantities of rain.

At each location, the gauges were sited in the most open area available, and away from overhanging foliage. The gauges at Anse Polymnie and Passe Houareau were the most sheltered, having *Casuarina* and *Cocos* trees 10–15 m tall within 20 m. At Dune D'Messe, two gauges were installed, one on the dune in the lee of the trade winds, and one on the exposed sea coast. The dune site appears to have been a sheltered one relative to the coastal one and to the Research Station.

The records have been summarized by comparing the data from each station to the data for the similar time interval extracted from the daily rainfall records kept at the Research Station. The out-station data have been expressed as percentages of the Research Station rainfall and are shown in table 1.

Table 1. Recordings of total rainfall around Aldabra as used in the present study

(Trade wind season is May–November; monsoon season is December–April.)

station	duration	no. of days	no. of recordings	rainfall†	rainfall for trade wind season†	rainfall for monsoon season†
Passe Houareau	5 April 1973–3 February 1975	669	74	90	65	102
Anse Mais	3 July 1973–27 February 1975	604	38	140	215	117
Cinq Cases	13 May 1973–9 October 1974	514	22	95	152	76
Dune d'Messe						
exposed	2 May 1973–6 May 1974	369	16	137	142	129
sheltered	10 February 1973–6 May 1974	450	13	61	39	80
Dune Jean-Louis	30 June 1973–8 September 1974	435	16	105	98	107
Anse Polymnie	9 November 1973–7 August 1974	196	25	134	121	135
Anse Gionnet	15 April 1974–19 October 1974	187	4	141	121	153
Anse Takamaka	28 February 1974–9 August 1974	162	7	114	63	122

† Expressed as a percentage of that at Ile Picard during the equivalent period.

Results

The duration and number of records for each site are given in table 1. Three sites had records covering less than one year and especial caution was necessary in evaluating them.

The data on spatial variation in rainfall are presented in table 1 as a summary of all records and also for the wet and dry seasons separately. The wet season was defined as the period December–April and the dry season as May–November, based on the long-term averages in Stoddart & Mole (1977).

The most obvious result found in table 1 was that there was heterogeneity in rainfall across the atoll in any season. Anse Mais, Anse Polymnie, Dune d'Messe (exposed) and Anse Gionnet consistently received more rain in all seasons than did the Research Station, while Dune Jean-Louis received about the same amount. Passe Houareau and Cinq Cases at the eastern end of the atoll, showed distinct but opposite seasonal variations in rainfall relative to the Research

Station. Cinq Cases received nearly 50 % more dry season rain than the Research Station while Passe Houareau received only 65 % as much. During the wet season Cinq Cases received only 76 % as much rain as Research Station but Passe Houareau received virtually the same amount. The dune site at Dune d'Messe was consistently drier than Research Station but was driest during the trade wind season.

The original data indicated that rainfall was heavy from moderate tropical depression 'Bernardette' at Research Station, Anse Polymnie, Anse Gionnet, Dune d'Messe, Dune Jean-Louis and Anse Takamaka. At Passe Houareau only 50 % and at Cinq Cases only 36 % as much rain was recorded as at Research Station over the period of the storm.

Discussion

Simultaneous records of rainfall at Passe Houareau and Settlement were first made by Farrow (1971). Subsequently, one year's records were collected by J. Frazier at Dune Jean-Louis (Stoddart & Mole 1977). Farrow's short run of observations served to show that rainfalls were not synchronous at the two ends of the atoll. Frazier's data indicated that yearly totals at two widely separated points on the atoll could differ by nearly 30 %. Stoddart & Mole (1977) concluded that higher rainfall totals at Dune Jean Louis were due to more frequent rainfall and not heavier falls than at Ile Picard.

The summary of all data now available supports Farrow's original observation that rainfall is variable across the atoll. Trans-atoll variation needs to be separated into that portion due to local factors and that due to regional ones. There does not appear to be any reason for expecting systematic patterns resulting from regional causes, because Aldabra is small in relation to the surrounding relatively empty and open ocean. The search for local patterns in rainfall on Aldabra, therefore, should be directed towards finding systematic trends for relative excesses and deficiencies that are correlated with geographic position around the atoll.

The trend of rainfall at Research Station is for most of the rain in any year to come from only a few heavy falls (90 % of rain days have less than 15 mm recorded (Stoddart & Mole 1977)). The data from regional storm 'Bernadette' indicate that even heavy falls are not necessarily recorded everywhere on the atoll at one time. Therefore it seems necessary to conclude that many years of simultaneous records will be needed before any trans-atoll patterns can be detected among the large apparently chance variations of a regional origin.

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