Watts, I. E. M.: Equatorial Weather, p. 129–143.
Yin, M. T.: A synoptic-aerologic study of the onset of the summer monsoon over India and Burma, Journal of Met., Vol. 6, 1949, p. 393–400.
(6) Dale, W. L.: Wind and Drift Currents in the South China Sea, Chart. 4.
Watts, L. E. M.: Equatorial Weather, p. 10.
(7) *Malayan Meteorological Service* – Summary of Observations, Volumes for 1953–1962, Singapore, various years.
(8) Nieuwolt, S.: op. cit., p. 2 and Fig. 5.
(9) Fisher, C. A.: op. cit., p. 38.
Dale, W. L.: op. cit. Charts 2–4.
(10) Dale, W. L.: op. cit. Charts 5–7.
Fisher, C. A.: op. cit., p. 38.
(11) Monthly Sea Surface Temperatures and Surface current Circulation of the Japan Sea and adjacent Waters, Air Ministry, London, 1944.
Li, T. S.: Sea Surface Temperatures for Hong Kong, Technical Note No. 5, Royal Observatory, Hong Kong, 1964.
(12) Letter dated 5th January 1965, from Director, Royal Observatory, Hong Kong.
(13) Watts, I. E. M.: Equatorial Weather, p. 11.
(14) Watts, I. E. M.: Equatorial Weather, p. 107–109.
(15) Dale, W. L.: opt. cit., Chart 8–12.
Watts, I. E. M.: op. cit., p. 10.
(16) Thompson, B. W.: op. cit., p. 586–588.
(17) Lautensach, H.: Ist in Ostasien der Sommermonsun der Hauptniederschlagsbringer?, Erdkunde, 1949, p. 1–18.
Lautensach, H.: Der hochsommerliche Monsun in Süd- und Ostasien und auf den angrenzenden Meeren, Peterm. Mitt., 1950, p. 18–24.
Pédelaborde, P.: op. cit., p. 139–141.
(18) Watts, I. E. M.: op. cit., p. 160–165.
Nieuwolt, S.: Das Klima von Singapur, Mitt. Österr. Geogr. Gesellschaft, Vol. 106, 1964, p. 157–178.
(19) Ramage, C. S.: Diurnal Variation of Summer Rainfall of Malaya, Journal of Tropical Geogr., Vol. 19, 1964, p. 61–68.
(20 Dale, W. L.: op. cit. Chart 1.
Watts, I. E. M.: op. cit., p. 11.
(21) Nieuwolt, S.: Rainfall Probability in Malaya, Fig. 4, 7, 10, 18.
(22) Nieuwolt, S.: op. cit., Fig. 18.
(23) Nieuwolt, S.: Evaporation and Water Balances in Malaya, Journal of Tropical Geogr., Vol. 20, 1965, p. 34–53.
(24) Nieuwolt, S.: op. cit., p. 34–39.
(25) Nieuwolt, S.: op. cit., p. 45.
(26) Nieuwolt, S.: Rainfall Probability in Malaya, Fig. 15.
(27) Ramage, C. S.: op. cit. Fig. 7.
(28) Thornthwaite, C. W. and Mather. J. R.: Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance, Centerton, N. J., 1957.
(29) Baver, L. D.: Retention and Movement of Soil Moisture, in Hydrology, New York, 1942, p. 364–384.
Terzaghi, K.: Soil Moisture and capillary Phenomena in Soils, in Hydrology, New York, 1942, p. 331–363.

RAINFALL SEASONALITY IN THE TROPICAL SOUTHWEST PACIFIC [1]

With 5 figures and 6 maps (supplement V)

E. A. Fitzpatrick, Doreen Hart and H. C. Brookfield

Zusammenfassung: Der jahreszeitliche Charakter der Niederschläge im Südwest-Pazifik.

Unter Verwendung der verfügbaren Niederschlagsmeßwerte von mehr als 1000 Stationen wurde eine Karte des durchschnittlichen jährlichen Niederschlages im Südwest-Pazifik gezeichnet und werden die meteorologischen und topographischen Faktoren des Niederschlages innerhalb dieses Gebietes diskutiert.

Für eine Zahl ausgewählter Stationen wurde außerdem der durchschnittliche monatliche Niederschlag genauer untersucht. Die Untersuchung ergab, daß mit wenigen Ausnahmen nicht mehr als zwei vergleichbare Zeitspannen notwendig sind, um einen hohen Prozentsatz der gesamten Variationsbreite der monatlichen Durchschnittswerte zu erklären. Die Auswertung der ersten und zweiten Periode vermittelt somit eine objektive Grundlage zur Abschätzung der durchschnittlichen Niederschläge für jede Woche. Diese Wochenschätzwerte sowie die Daten, die mit dem Höhepunkt und Tiefpunkt des jährlichen durchschnittlichen Niederschlagsablaufes zusammenfallen, wurden festgestellt und in die Karte eingetragen.

Die Wochenschätzwerte ergeben sieben ausgeprägte Typen des jährlichen Niederschlagsablaufes. Ihre geographische Verteilung und die allgemeinen Zusammenhänge zwischen der räumlichen Verteilung der Ablauftypen mit Zügen der pflanzlichen und menschlichen Ökologie des Gebietes werden aufgezeigt.

Das Ergebnis dieser Analysen macht die Lücken in unserem Verständnis der Zusammenhänge zwischen den allgemeinen geographischen, den meteorologischen und topographischen Zügen und dem festgestellten jahreszeitlichen Charakter des Niederschlages im Südwest-Pazifik deutlich. Der Mangel zureichender Meßdaten sowohl in Bodennähe als auch aus den oberen Luftschichten erschwert jedoch eine Vertiefung unserer Kenntnisse durch klimatologische Analyse in diesem Bereich.

1. Introduction

In the oceanic region north of Australia and New Zealand is a chain of mountainous islands that spans almost the full distance from the Equator to the Tropic of Capricorn. Together with the Indonesian archipelago lying immediately to the west, the northern part of this region is one of the wettest parts of the earth's surface; few areas fall more obviouslv into the 'Humid Tropics' by whatever means of classification we employ. Yet detailed rainfall data that have become available in recent years reveal a wide variety of climates, and in particular, a wide variety of rainfall regimes.

[1]) The authors wish to thank Mrs. B. Banks Mrs. A. Komarowski and Mrs. A. Johnson who assisted in the collection and preparation of data. Thanks are also due to the Commonwealth Scientific and Industrial Research Organization and the Australian National University for their kind help in financing the printing of the maps.

In the course of preparing a general work on the Melanesian territories, BROOKFIELD became interested in the significance of climatic variations within areas formerly presumed to be uniformly wet. As MOHR (1933) has pointed out with regard to Indonesia, the potential of areas with greater seasonality, and especially with periods of moderate drought, is often greater than that of continuously wet tracts. The possible significance of climatic variations in explaining the distribution of human occupance is clearly brought out in New Guinea, where the overwet areas are shunned, and a high proportion of the population lives in country with marked seasonal contrasts in rainfall (BROOKFIELD 1965). Following the application of harmonic or Fourier analysis to mean monthly rainfall data by HORN and BRYSON (1960) in the United States, SABAGH and BRYSON (1962) in Canada and FITZPATRICK (1964) in Australia, we decided to see whether similar techniques could be used assess seasonality in this entirely tropical region. Hart has carried out a large part of the basic work required, and has interested herself particularly in the relative significance of meteorological and topographical controls. The present paper summarizes the product of our joint work and discussions, and is presented as an essay in tropical climatology.

Suppl. V A shows the areal pattern of mean annual rainfall within the region. This map was constructed from all available data from over a thousand stations. Total falls outside Australia are almost everywhere high, being less than 50 inches only in western New Caledonia and the coast of central Papua. Nonetheless there is great variety. A belt of very high rainfall extends through the central mainland of New Guinea to the south of the southern crests of the main cordillera and continues east into the Huon peninsula, New Britain and Bougainville. On the other hand, annual falls above about 125 inches are the exception rather than the rule south of latitude 10° S, and there are significant tracts with lesser rainfall well to the north of this latitude. Of particular note are (a) the inland New Guinea dry zone, in the system of valleys lying west of Huon gulf and extending far west into the central cordillera, and (b) the dry pockets along the north coast of New Guinea and extending inland, especially the wide area in the Sepik valley south of Wewak, and an area of the remarkably low rainfall on Waigeo Island, virtually on the equator. The dry pockets of the northern coast continue westward into Indonesia, culminating in the Palu valley of Sulawesi (Celebes) which has an annual mean of only 11 inches. Were data adequate, more variation would be revealed on individual islands and in the interior of New Guinea. In Suppl. V A and throughout this study many of the isopleths are interpolated on the basis of general field knowledge of existing vegetation cover.

II. Meteorological and topographical controls

Until very recently the only texts to deal specifically with the climate of the territories with which we are concerned were those of BRAAK (1921–29), the BRITISH NAVAL INTELLIGENCE DIVISION (1945), and HOUNAM (1951). From these works a popular concept of the general circulation of the area has evolved. The southwest Pacific has traditionally been envisaged as an area where a more or less continuous belt of low pressure – "the doldrums" – coincides with the zone of maximum insolation, and separates the southeasterlies – "trades" – to the south from the "northwest monsoon" to the north. The whole system had been seen to have an annual march latitudinally, and observed annual regimes of rainfall and other climatic elements have been associated with these periodic displacements. Following this scheme New Guinea and adjacent areas are described as having a "southeast season" attaining its peak in June and July, and a "northwest season", most strongly developed in January and February. This interpretation is founded on observations of surface winds which, by themselves, are now generally recognised by meteorologists as wholly inadequate as a basis for climatic interpretations.

During the second world war a small amount of upper air data was collected for tropical areas in the Pacific, and these data have shed considerable light on the nature of the general circulation in the region. Unfortunately, detailed analysis of these data has lagged far behind their collection. The traditional explanation of broad climatic controls is now generally recognised as inadequate (CURRY and ARMSTRONG 1959), and it remains for the new information to be correlated with the growing amount of surface data available from the area.

The concepts of a continuous "doldrum" belt, and the predominantly westerly circulation during the early part of the year have arisen, according to PALMER (1951), from the study of mean surface pressure and wind conditions rather than individual synoptic situations. For the purposes of this study, the most satisfactory interpretation of Pacific circulation follows the adapted perturbation theory proposed by PALMER and by THOMPSON (1951). The basic flow of the tropics is taken to be easterly, with perturbations of the easterly wave type as found in the Caribbean (e.g. MERRIT 1964), occuring on either or both flanks of the line which is thought of as the intertropical convergence zone (ITCZ). THOMPSON affirms that in this part of the Pacific fragmented portions of ITCZ do occur, often between successive vortical circulations which are found to the north of New Guinea. These vortical circulations are seen as having a characteristic westward movement with westerly winds occurring in their northern sectors. These vortices are essentially a part of the surface circuation: THOMPSON has found that in southeast Asia they occur most frequently at the 2,000 feet level and are rarely found above 10,000 feet. This implies that the mountainous regions of New Guinea are only indirectly affected by the vortices and that in their place irregular zonal flow can be found. South of the perturbation belt occur the 'trade winds' or the 'southeast variables' referred to by PALMER. However, it would seem that the southeasterlies rarely penetrate the mountain mass, and then only in a highly modified form (ASHTON 1946; BRAAK 1923).

The relative dominance of the southeasterlies and the perturbation belt varies with season and with the latitudinal position of each island group. The southeasterly airstream penetrates far to the north in June, July and August, while in January and February equatorial air masses are at times found southward of New Caledonia.

During the latter season there is a tendency for tropical cyclones to develop over the triangle of ocean whose apices are the Ellice Islands, Fiji, and the New Hebrides, more rarely extending northwestward into the Solomons. The yearly occurrence of these cyclones is irregular, but their tracks are well marked in a broadly southwesterly direction. Thus a high percentage of the storms pass over, or nearby, Fiji, the New Hebrides, and New Caledonia. The average number of tropical cyclones per annum is three, and though their duration is short, they nevertheless can have an important effect on the monthly means of rainfall in this region (GIOVANELLI 1952). During the winter the southern islands are also affected by the passage of meridional fronts from west to east across the Tasman Sea. New Caledonia receives significant rainfall from these fronts in June and July. There seems also to be a correlation between the passage of meridional fronts and the development of convergence zones within the southeasterly stream at lower latitudes, bringing concentrated spells of heavy rain during the southeast season as far north as New Britain (A. DOUGLAS, personal communication).

Differential heating of land and sea is of considerable importance throughout the area, convectional rainfall contributing a large share of the total precipitation. Any large island is a complete heat engine and forms its own convective cell (MALKUS 1955). From experience of forecasting in the tropics, ASHTON (1946) estimates that an island with relief of no more than a few hundred feet need only be 15 miles across for a local wind to develop. Writing specifically of the trades, but with a wider application, MALKUS confirms that an island serves to intensify some of the processes normally at work in a wind system and to depress others. By altering the balance of these processes it accelerates results which would otherwise occur imperceptibly over a long oceanic trajectory.

When the southeasterlies blow, windward and lee effects are marked over the whole southwest Pacific. Some of the driest conditions in the region are to be found at this time on the west coast of New Caledonia, while the east coast receives relatively high rainfall from forced uplift and induced instability, in spite of the low moisture content of the southeasterlies at this latitude. In this season the southern islands generally receive comparatively little rain, and the orographic effect becomes marked only on the mountains or where high ground rises directly behind the coast. Further north, even low windward shores receive very heavy rain, since the southeasterlies become more moist and warmer at low levels in the course of their equatorward trajectory. Along the parallel 10° S the rainfall yield from onshore southeasterlies diminishes markedly from the Solomons west. East of Papua the southeasterlies have a strong equatorward component, but westward through the Arafura Sea they are curved along the parallels. The dry coastal belt on either side of Port Moresby (Suppl. V A) is not so much the result of a lee effect as of the failure of the low coasal land area to present an adequate barrier to the southeasterlies; here the alignment of the coast is either parallel to or slightly divergent with respect to the prevailing wind. However, to the northwest of Port Moresby at the head of the Gulf of Papua, very high rainfall occurs owing to the presence of a mountain barrier which is adequate to induce instability. Because of stagnation against the face of the upland, very high rainfall is experienced not only along the southern slopes and summits of the mountains but also on the plains for about 100 miles in front of the ranges. High rainfall over the southern side of New Britain can be attributed to the same factors.

Dry lee belts are formed on the northern edge of the New Guinea cordillera, in enclosed basins within the mountains, and on the northern sides of such high islands as Guadalcanal and Viti Levu over that part of the year when southeasterlies most strongly dominate the circulation. The almost complete absence of a counterpart to these lee belts during the so-called northwest season is evidence that there is no single dominating and sustained northwesterly circulation at this time of year.

III. Rainfall data and analytical procedures

Our data are drawn from a variety of sources. Records for 392 gauges in Australian New Guinea, and a smaller number of gauges in the Solomons and New Hebrides, are held on punch cards in the Commonwealth Bureau of Meteorology, Melbourne; these have been extracted to the end of 1963. Some additional records for these territories were obtained from the Commonwealth Department of Works, the Solomon Islands Department of Agriculture, and Lever's Pacific Plantations Pty. Ltd. Before the transfer of power to Indonesia, the Dutch authorities in West Irian maintained a total of 439 gauges, and published returns annually up to the end of 1960. The New Zealand Meteorological Service in Fiji publishes full records of 181 gauges in that Colony, and in other Pacific territories to the east and north. The Service Météorologique of the Ministère de la France d'Outre Mer publishes annual returns for all French Pacific territories, including New Caledonia and one station in the New Hebrides. All these authorities have freely made their records available. A selection of 235 stations was made for the purpose of this inquiry. The results of harmonic analysis of 35 northern Australian stations (FITZPATRICK 1964) were also included for purposes of comparison.

The records for selected stations were divided into two groups: a control group, consisting of 98 stations for which long records (20 years or more) are available, and a group of 194 stations with shorter records covering the 7-year period, 1954–1960 (Fig. 1). Some stations are common to both groups. In dealing with stations having only the short records, it was considered essential to use monthly means calculated over a standard period to obtain the best appraisal of areal differentiation in rainfall characteristics. From a preliminary examination of the results of harmonic analysis applied to monthly means for stations common to both groups, it was found that the curves fitted to the data differed most markedly where very high means occurred (see Fig. 4). Nevertheless, it was considered that agreement was sufficiently close to warrant using the 7-year means where no longer records existed. We cannot pretend that this is wholly satisfactory. Using the data of a number of stations, a method developed by LANDSBERG (1951) for assessing the adequacy of means and medians shows that between 23 and 29 years are required to develop a stable median in the southwest Pacific and slightly longer to develop a stable mean. However, we have fewer than 5 stations outside Australia with records that are continuous through the second world war. The greatest number of stations recording in any pre-war year is 72 in 1936, and not until 1954 when the Dutch began collation of the West Irian records, does the total number of gauges first exceed 100. To have demanded a longer standard period than the seven years, 1954–60, during which the Dutch records are available, as well as a sufficient density of stations from other areas, would have required exclusion of all of West Irian and also most of inland Australian New Guinea, the New Hebrides, and the Solomon Islands. Even for this limited standard period, data for particular months were not available[2]). In view of the paucity of stations with long-period records in most areas, this source of weakness has to be accepted: it will be several years before any more satisfactory result can be obtained over most of the area, and for West Irian no improvement is possible, as reports have ceased.

Data were entered on punch cards, and programs for digital computers developed by FITZPATRICK[3]) were used to carry out all computations.

Details of the principles underlying harmonic analysis are given in many standard texts, (e.g. CONRAD and POLLAX [1951], BROOKS and CARRUTHERS [1953]), and the use of this technique is described in each of the applications previously cited. The method, as applied here, is therefore only briefly described in general terms.

A series of simple sine curves (harmonics) are fitted by least squares to the twelve values of mean monthly rainfall (R). The first curve of the series, i.e. the first harmonic, has the form of a simple, single-cycled curve rising above the mean of the twelve values ($\bar{R}$) over half of the year and falling below the mean over the remaining half. Similarly, a series of multiple-cycled curves are fitted to the data. As successive harmonics are combined to produce a Fourier series the points on the resultant curve progressively approximate

[2]) In these cases, provided that values were missing from a given month only once during the seven years, and providing also that not more than two months were missing in any one year, the mean monthly values for the six remaining years were substituted.

[3]) Programs are written in *Fortran* for processing on the IBM 1620 or CDC 3600 computers. Details of these programs are available on request.

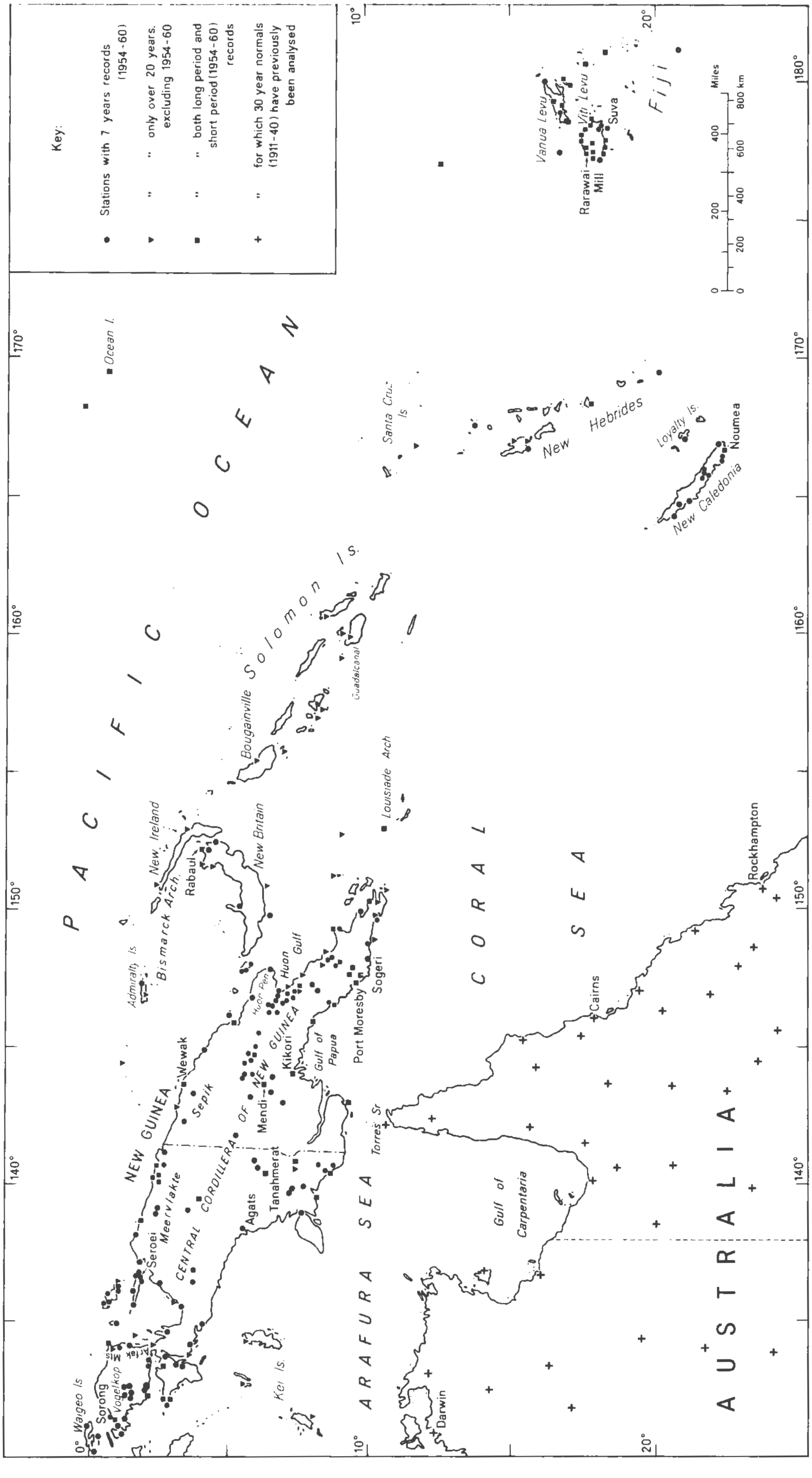


Fig. 1: Location of rainfall stations and place names referred to in text

the monthly means. The equation for the curve has the form:

$$R' = \bar{R} + A_1 \sin(30°X + \Theta_1) + A_2 \sin(60°X + \Theta_2) + \ldots A_6 \sin(180°X + \Theta_6)$$

Where R' is the point on the curve corresponding to R, A_K and Θ_K are the amplitude and phase angle of the Kth harmonic, and x is the month identification, commencing with January equal to zero and continuing to December equal to eleven. Thus as the number of harmonics included in the series is extended, complex annual regimes can be simulated, and an increasing proportion of the observed total variance of the monthly means about the mean of the twelve values is accounted for statistically. A large proportion of this total variance is thus associated with the first harmonic if the curve is characterised by a single crest and a single trough, or by the second harmonic if it displays two distinct maxima. On the other hand, when there are no marked cyclic annual or semi-annual trends in the monthly means, the relative contributions of the first and second harmonics to the total variance are small. The bulk of the variance is then related either to physical controls which are active only over a month or two at a time, or to purely random factors.

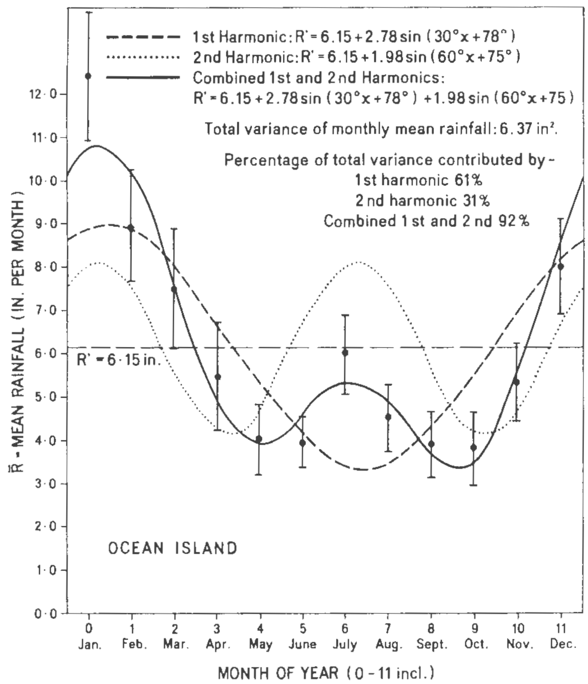


Fig. 2: Application of harmonic analysis to the long-term mean monthly rainfall data for Ocean Island
Vertical lines indicate the range of one standard error of the mean

One of the advantages of harmonic analysis as applied here is that it provides an entirely objective means of isolating and expressing quantitatively the broad character of the rainfall regime as distinct from those short-term variations between months which reflect other than seasonally operative controls. The variance contribution of a known harmonic can be readily evaluated from known amplitudes, and thus the percentage of the total variance accounted for by the harmonics individually and combined can be determined. This provides a basis for assessing the relative strength of the controls which act over an annual or semi-annual cycle.

An application of harmonic analysis with mean monthly rainfall is illustrated in Fig. 2 using the long-term means for Ocean Island. It can be seen that taken individually neither the first nor the second harmonic depicts the annual regime with adequate precision, but nonetheless each makes an appreciable contribution to the total variance[4]). When the two harmonics are combined, a good simulation of the observed regime is achieved. The curve of the combined harmonics accounts for 92 per cent of the total variance of the twelve values of R.

IV. Discussion of results

Our purpose here is to use harmonic analysis to yield an objective basis for the areal differentiation of seasonality. Though we are not unconcerned with explaining the patterns revealed, it will be clear that the bases on which any satisfactory explanation could rest are almost wholly lacking. Therefore, in turning to a discussion of our results, we are drawn to consider them mainly as descriptive climatology. In Figs. 3, 4 and Suppl. V B–E we attempt to portray in cartographic form some of the more salient parameters obtained by harmonic analysis. With this end in view, and to overcome the cartographical limitations of map reduction as applied to very small islands, we have employed shading patterns in addition to isopleths: this may do violence to some canons of cartographic treatment of such data, but no alternative seems suited to an intricately diverse region of small islands and high mountains.

The observed total variance of mean monthly rainfall and the proportions of this total that are associated with the first and second harmonics

[4]) It should be noted that as used throughout this paper the term, v a r i a n c e, refers to the extent of the variation of the monthly means about the mean of the twelve monthly values, and n o t to the variation of specific occurrences within the sequence of observed monthly rainfall totals.

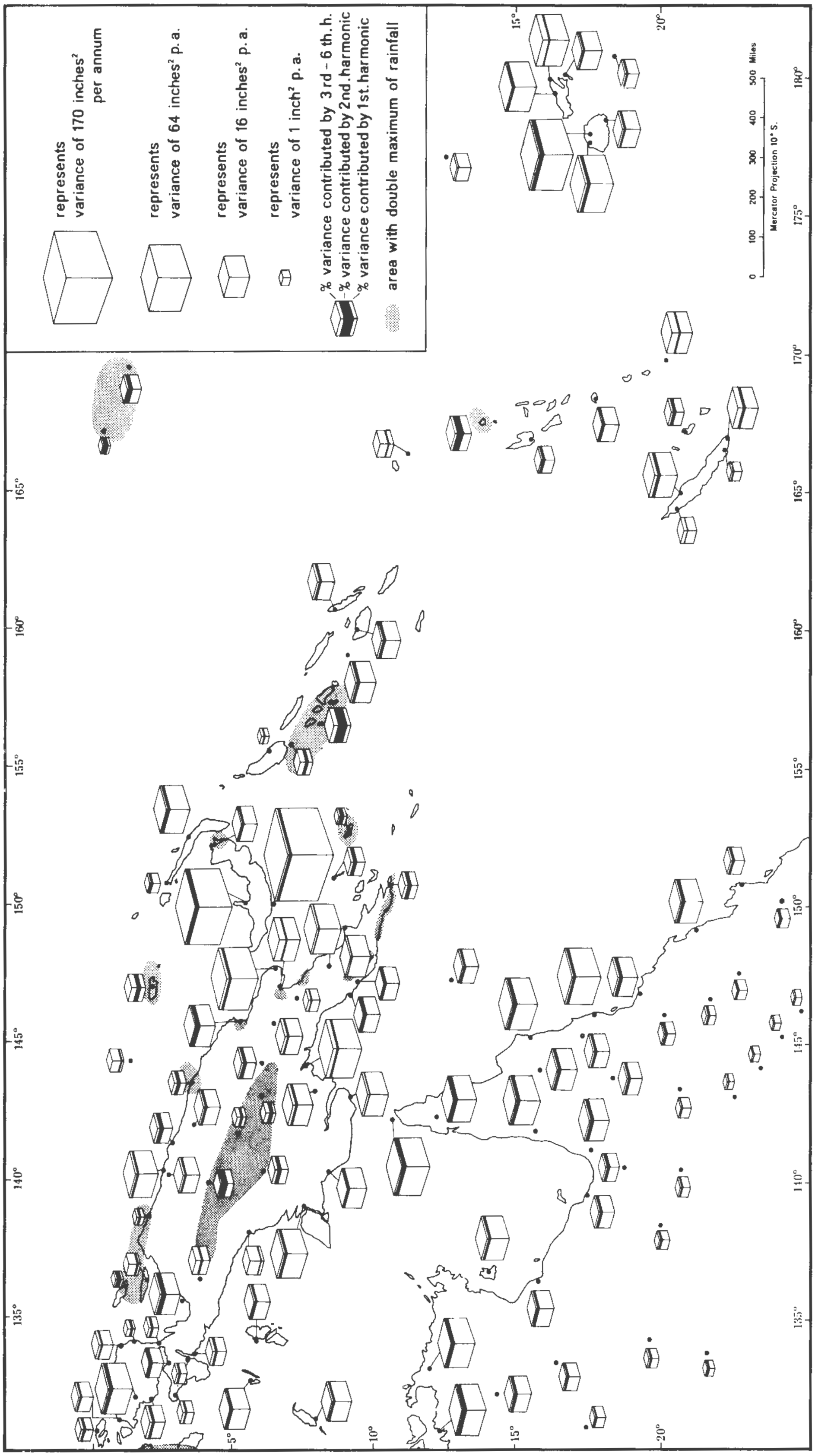


Fig. 3: Total variance of the twelve monthly means of rainfall and the percentage of this total contributed by the first, second, and higher harmonics

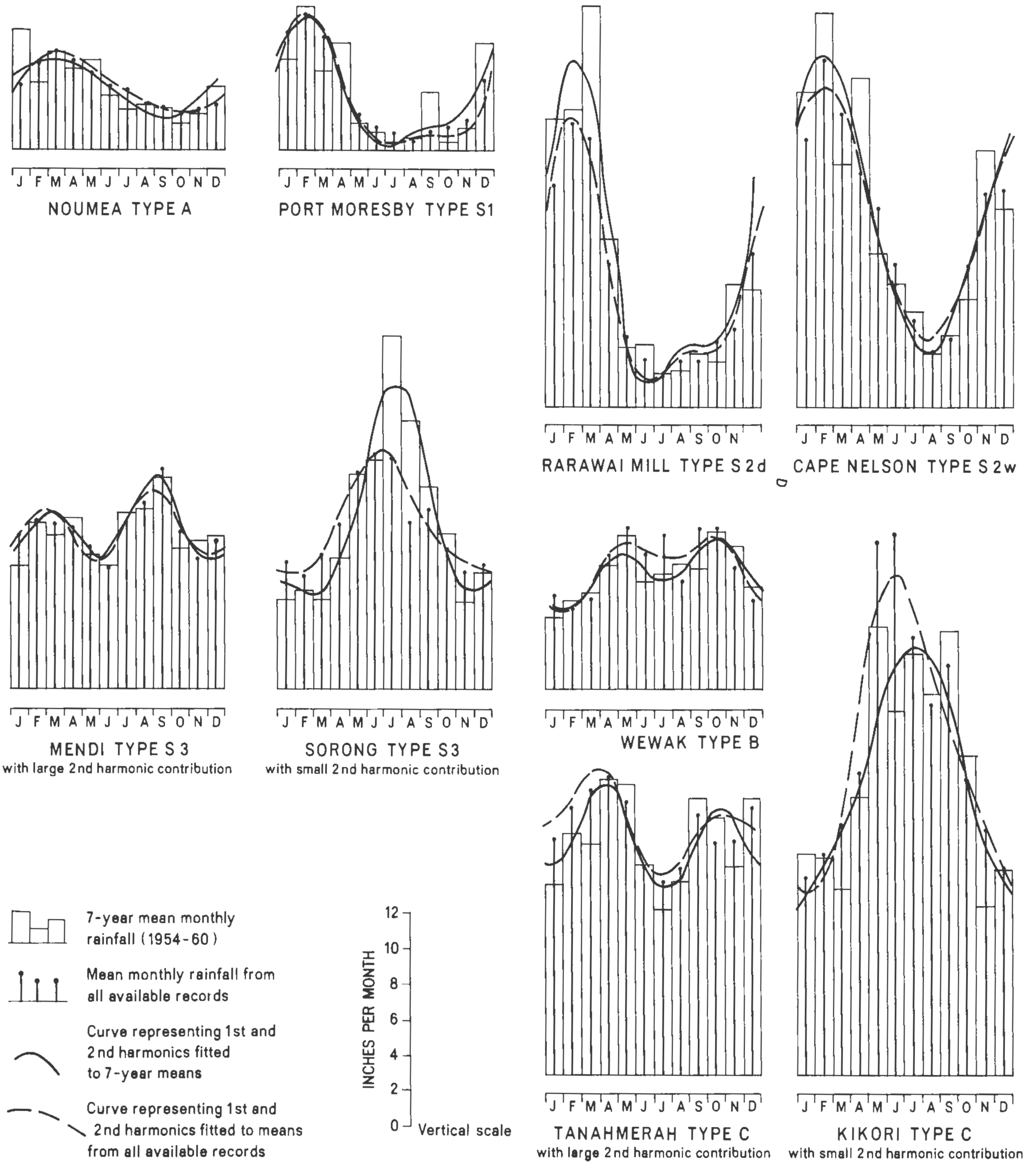


Fig. 4: Typical rainfall regimes for selected stations in the Southwest Pacific

are shown in Fig. 3. In Australia and New Caledonia there is an obvious correlation between total rainfall (Suppl. V A) and total variance, but throughout the remainder of the area no such generalisation can be made. For example, among tracts experiencing high rainfall, New Britain has high total variance while the southern part of the central New Guinea cordillera has very low variance. By contrast to Australia and New Caledonia, elsewhere in New Guinea, the Solomons, northern New Hebrides, and Fiji, many areas of high rainfall have relatively low variance. Almost everywhere where total variance is high, by far the largest proportion is associated with the first harmonic, showing a marked tendency for rainfall concentration in a single period of the year. In general, where the contribution of the first harmonic is small, that of the second harmonic – indicating a tendency towards double maximum – assumes equal or greater relative significance, and in all these areas the total variance is small. Particular areas of low variance stand out: central New Guinea, eastern Papua – western Solomon islands, Geelvink Bay, Manus, and Ocean Island. Only at the few island stations of Seroei, Pelleluhu, and Vanikoro, and at Agats on the mainland do the higher harmonics contribute a major part of the total variance, which is itself very small.

Fig. 4 exemplifies the distinctive seasonal patterns occurring within this area. Both long-term and 7-day mean monthly rainfalls for nine widely separated stations are shown, and curves obtained from a combination of the first and second harmonics fitted to each of these sets of monthly means are also given. It can be seen that generally good agreement is achieved between the curves and the means without the necessity for the inclusion of more than the first and second harmonics. The diagram for Port Moresby is of special interest, since it demonstrates how isolated erratic values in the annual sequence of means, which are not uncommon when short periods are used, are largely eliminated in the fitted curve. The original monthly data show that the singularly high mean value for September is due to the occurrence in 1958 of three consecutive days over which 10.79 inches of rain were recorded, making the total for that month over 13 inches.

Fig. 4 clearly illustrates the wide variation in regimes, and also the marked contrasts in the relative strength of annual and semi-annual tendencies. The dates corresponding to the crests and troughs are of particular value as climatological parameters, as is also the average amount of rainfall at these wettest and driest times of the year. In order to refine these parameters, the curves of all stations were evaluated at weekly intervals. The results of these evaluations are shown in Suppl. V B-E.

Suppl. V B shows the date of occurrence of the week with the highest mean rainfall obtained from the combined curve of the first and second harmonics. Over all the area lying poleward of 10° S, and over large areas to the north of this parallel, this maximum occurs during the first 12 weeks of the year, with surprising uniformity over very wide areas. No evidence at all of an advancing monsoon-type crest as postulated by Hounam (1951) is revealed on the map; the crest in north-central New Guinea occurs in almost exactly the same week as in Fiji, New Caledonia, and the New Hebrides, and is, if anything, slightly later than the crest in central and northern Australia except on the Queensland coast near Cairns. Only on coasts and slopes exposed to the southeasterlies and lying north of latitude 10° S does the primary crest occur at the peak of the southeast season in June-July.

The mean rainfall of this maximum week, irrespective of the date of its occurrence, is shown in Suppl. V C. Areas of very heavy seasonal rain are clearly picked out in the central New Guinea–New Britain area, though there is nothing on the northern side of the central cordillera to correspond with the high falls received during January-March in northern New Britain. The dry zones, evident in Suppl. V A are, however, sharply differentiated on this map. All but one of these dry zones have relatively low maximum rainfall; the northern side of Fiji, on the other hand, is classed among the wettest areas of the southwest Pacific at this time. Noteworthy also are the high peak falls along the narrow zone of the northeast Queensland coast, making this area environmentally more akin to the tropical areas to the north than to the Australian continent generally.

Suppl. V D shows the date of occurrence of the trough, or mean driest week. In areas with a pronounced single maximum, this point is separated by roughly six months from the crest point, but there are numerous divergencies in areas where a tendency to a second maximum occurs. Thus the trough has a mid-year date over almost all of northern Australia, in both the far south and in north-central New Guinea, in Fiji and the New Hebrides, northern Guadalcanal, and northern New Britain, while the trough occurs in the first weeks of the year in southern New Britain, around the Huon Gulf, at the southeastern tip of Papua, in the central Vogelkop, and on the "weather coast" of the larger islands of the eastern Solomons. But it occurs during the last three months of the year in quite wide adjacent areas, especially across south-central New Guinea, along the northern coast of New Guinea, and in most of New Caledonia and the southern islands of the New Hebrides. In the two latter areas this is explained by the rainfall received from meridional fronts in June and July; these fronts retreat southward after August. At lower latitudes the widespread occurrence of a minimum in the last three months reflects the prevailing weather of this variable season; at this time vortical circulations are particularly prevalent, giving rise to alternate periods of very wet weather with mainly westerly movement of air, and periods of dry weather characterised by stable easterly airstreams, moving perhaps from the dry zone of the central Pacific. Prolonged incidence of this easterly air into the early months of the year can, on occasion, give rise to droughts in northern New Guinea, leading either to a 'late wet' or even to total failure of the 'wet'.

In Suppl. V E is shown the mean rainfall associated with the trough week. Nowhere in the islands is the trough week as dry as at almost all stations in north Australia, where its mean weekly rainfall is virtually zero. Very low falls are however experienced in all the dry zones, and in quite wide areas adjacent to them in northern New Guinea – even in the Huon peninsula and New Britain, in New Caledonia and the New Hebrides, and throughout Fiji except in south-eastern Viti Levu. On the other hand, the 'driest' week is very wet along the southern face of the central cordillera of New Guinea, especially toward the western end of this belt, and in the Vogelkop, Manus, and quite large parts of the Solomons.

V. Classification of regimes

The range between the crests and the troughs is thus highly variable over the area, but of itself this characteristic has limited ecological significance. Rainfall at the driest time of the year may yet be more than sufficient to sustain rain forest and even inhibit agriculture (e.g. Kikori, Fig. 4); conversely rainfall at the wettest time of the year may barely satisfy evaporation requirements (e.g. Noumea, Fig. 4) or, within the truly arid regions of Australia, fall far short of the water requirements of all but the most drought-tolerant species.

It would be most advantageous to classify regimes in terms of the length of time that the combined curve including the first and second harmonics are above or below the prevailing evapotranspiration requirements. However this is not practicable within this area since the spatial and seasonal variation of neither evapotranspiration nor evaporation is known in any detail. From estimates of total rainfall over catchments in the Sogeri Plateau area of Papua and a comparison of these with stream discharge records, and from both observed and estimated evaporation at Port Moresby, we have evidence that the potential rate of evapotranspiration varies seasonally and spatially within this area between 1.0 and 2.0 inches per week. These limits are in agreement with maps of net radiation given by Budyko (1956), and therefore we accept them as a rough, but not entirely arbitrary basis for distinguishing three levels of rainfall: –

Heavy (wet)	over 2.0 inches per week
Intermediate	1.0–2.0 inches per week
Light (dry)	under 1.0 inch per week.

Mean rainfall regimes may be such that one, two, or all three of these conditions are satisfied during the year, and stations can therefore be classified according to the length of time in each category. Classification is facilitated by the triangular nomogram in Fig. 5. The apices of the

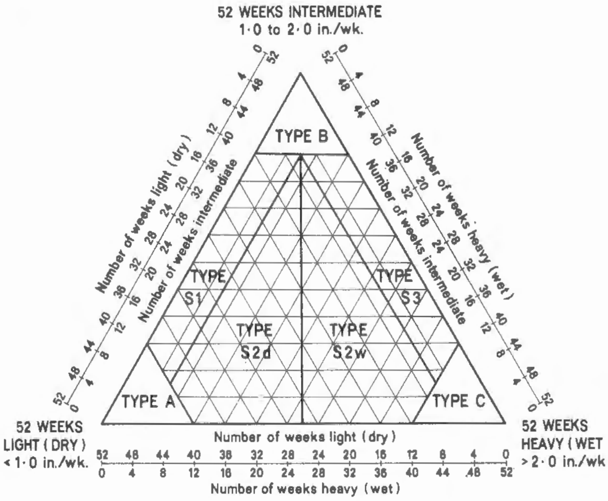


Fig. 5: Nomogram for the determination of regime types

triangle represent the cases where rainfall remains in the heavy, intermediate or light classes throughout the year, and the centre of the triangle represents the unique case where the three classes are equally shared in time. Thus by appropriate scaling any regime can be identified by its position within the triangle. Though the limits are inevitably arbitrary, the following basic regime types, of interest from an ecological viewpoint, can be recognised reading clockwise around the perimeter of the nomogram:

Regime Type	*Characteristics*
A	Continuously dry
S 1	Moderate seasonal alternation, intermediate to dry
B	Continuously intermediate
S 3	Moderate seasonal alternation, wet to intermediate
C	Continuously wet
S 2 w	Large seasonal alternation, wet to dry (with short dry season)
S 2 d	Large seasonal alternation, wet to dry (with long dry season)

In the legend on Suppl. V F, these classes are regrouped in a more ecologically meaningful sequence. Frequencies of heavy (wet), intermediate and light (dry) weeks were determined from the mean weekly rainfalls evaluated from the curves including the first and second harmonics. The map is highly generalised and many small occurrences of one type are included in a large area of an adjacent type. There are possibly larger omissions: almost certainly there is an area of type S2d (large range, with a long dry season) in the Meervlakte plain of interior north West Irian, but there are no recording stations in this area by which it might be identified.

VI. Geographical distribution of regime types

All the possible seven regimes as defined above are represented in the southwest Pacific area. The continuously dry regime, type A, is mainly represented in inland Australia, but there is a small occurrence along the western coast of New Caledonia (e.g. Noumea, Fig. 4). The gradient of regime types in this island strikingly resembles that experienced from the coast inland in north Queensland, and demonstrates the effectiveness of the dominating anticyclonic conditions at latitude 20° S, combined with the rainshadow effect of the central mountain chain of the island as inhibitors of rain even under strongly maritime influences.

The regime type S1, having seasonal alternation between light and intermediate rainfall (e.g. Port Moresby, Fig. 4) occurs principally along the margins of type C, but also in several isolated areas of Papua-New Guinea. Its presence in a narrow zone across northern Australia and in centralwestern New Caledonia and the Loyalty Islands may be interpreted as an indication of the effective southern limit of penetration of moist equatorial air southward in the summer season. North of latitude 10° S this regime type occurs only where orographic conditions cause strong sheltering from prevailing winds as in the inland New Guinea dry zone and the eastern Vogelkop, or perhaps divergence as on the central Papuan coast. However the isolated occurrence on low-lying Waigeo Island is anomalous.

Regime type S2d, exemplified in Rarawai Mill (Fig. 4), has large seasonal contrasts in rainfall, the range being from light to high, the period of light rainfall being of longer duration. This type occurs in a broad zone across the north of the Australian continent, southern New Guinea and the Kei islands, and is the regime of most of the windward side of New Caledonia. These areas all experience heavy rainfall associated with tropical low pressure systems of varying intensity originating in the zone of vortical circulations during the summer months. During the low-sun period, this same belt is dominated persistently by dry, stable air of southeasterly flow associated with anticyclonic centres lying mainly between 25° S and 30° S. (Karelsky 1956) S2d occurs also in four areas north of 10° S in New Guinea, on the north coast of Guadalcanal, in the Solomons, and on the northern sides of the two larger islands of the Fiji group. Exposure to the north and west, complemented by shelter from the south and east, is a satisfactory explanation in the southeast Papua, Guadalcanal and Fiji areas. The areas in central Papua and on the eastern fringe of the inland New Guinea dry zone are more strongly seasonal phases of the adjacent areas of type S1, the alternation being from heavy to light rather than from intermediate to light rainfall. Inland from Wewak, S2d occurs in the interior plain and adjacent rising south-facing slope, slightly sheltered from the north, yet the dry season is in the low-sun period. Further, there is little evidence that the southeasterlies are an effective meteorological control this far north and west. This is part of the general, highly intriguing problem of the very sharply contrasted climates found along the northern coastlands and inland of New Guinea.

Associated with the types S2d and S2w in terms of their potential, are the four small areas in which type B occurs (e.g. Wewak, Fig. 4). These tracts of continuously moderate rainfall, with only rare occurrence of either drought or drenching rains, are in New Guinea, and in Fiji, on the margins of the dry zone and are too small to be mapped. The Wewak coastal area in northern New Guinea is clearly associated with the S2 areas lying immediately south over the ranges. The most important of these tracts is, however, the Rabaul area at the northern tip of New Britain, where variable but moderate rainfall in a pocket sheltered from east, south and west alike coincides with a young volcanic soil of moderate fertility and high porosity. These small areas are climatically of interest by their rarity: in tropical maritime regions there tends to be a sharp transition between conditions favourable either to high or light rainfall. This is in marked contrast to many maritime environments at higher latitudes where high annual totals are more often the product of continued rainfall at an intermediate level throughout the entire year.

Regimes which range from moderate to heavy rainfall (type S3) are very extensive in the insular areas of the southwest Pacific. They are essentially transitional between S2d and S2w on the one hand and C on the other. Rainfall, even during the driest time of the year, rarely falls appreciably below requirements for free-water evaporation. In general, areas having this regime type experience considerable orographic convectional rainfall, and this is augmented either during the high- or low-sun periods, (e. g. Sorong, Fig. 4) or locally at two periods (e.g. Mendi, Fig. 4), to give a distinct seasonal concentration.

Type C is characterised by continued high rainfall over the entire year. Comparison of Suppl. V B and V D will show that this regime type is not associated exclusively with any one time of rainfall crest. As in S3, both single and double crests occur as typified at Kikori, and Tanahmerah respectively, (Fig. 4); however the quantity of rainfall is greater throughout. In the New Guinea mainland type C is most extensive over a zone along the southern foothills of the high central range. The high mountain barriers facing the southeasterlies induce a maximum rainfall during the low-sun period, a feature which reflects strong orographic lifting of the very moist air masses impinging on these areas after a long oceanic traverse from the anticyclonic centres between 25° and 30° S during the southeast season. In addition, during the high-sun period moist equatorial air with variable but dominantly westerly circulation brings rain to all areas north of 20° S.

The occurrences of type C in eastern Geelvink Bay and the adjacent mainland, in the northern Bismarcks, northern Solomons, Santa Cruz group, and in Rotuma and Ocean Island north of Fiji reflects the dominant prevalence of equatorial air at all seasons in these latitudes, and the very moist character of such modified southeasterly air as reaches these regions. By contrast, type C is totally absent from Australia, New Caledonia and the southern New Hebrides, since the southeasterly stream is here dry and stable, and since such equatorial air as extends south during the high-sun period is modified, giving rise only to limited periods of heavy rainfall. In Fiji, we find the most southerly occurence of type C. During the high-sun period these islands receive very heavy rain throughout, there being no marked lee effect at this season.

Comparison of Suppl. V F with the plant and human ecology of the region shows some interesting relationships which reinforce our hope that this classification, or some modified form of it, may have ecological value in low latitude environments. Native vegetation in type A is generally xerophytic; at best there is no more than dry savannah along its wetter margins in Australia and in its restricted occurence in New Caledonia. In the island regions, grasslands and areas of *Eucalyptus*, *Melaleuca* (New Caledonia), and *Acacia*, or mixed savannah, are confined to types S1, S2d and S2w, with the exceptions being some areas in type S3 in the New Guinea highlands, and in the alpine grasslands whose rainfall and temperature characteristics are not well known. Most of these grassland areas, except possibly the alpine grasslands, seem to be the product of human interference, especially by the agency of fire. None the less grasslands are almost entirely confined to areas having at least a short spell of light rainfall. The prevailing type of vegetation of types B, S3 and C is everywhere rain forest.

In terms of the human use of land, particular attention is focused on the seasonal regimes, S1, S2d, S2w, S3, and on type B: most of the population of the area lives in regions experiencing these climates, and about one-third lives in the valleys of the New Guinea cordillera experiencing types S2w and S3. In these same regions are the areas giving highest yields of most field crops and tree crops, especially of copra, which is the staple commercial crop of most island areas. Regime types S2d and S2w may well have unique agronomic potential since successful maturation and harvesting of crops often depends on the occurrence of a distinctively dry period within the annual regime. Few areas of type C are closely settled; this country, with continuous leaching of the soil, mud and rank growth of vegetation, offers far greater difficulties for human occupance than areas having marked seasonal regimes, or continuously intermediate rainfall.

VII. Questions arising

A significant feature of the distribution of climatic regimes over the area, revealed on each of the maps, but especially on Suppl. V F, is that though on the whole these regimes lie in roughly parallel belts, the belts have an east-southeast to west-northwest orientation. This is in marked contrast to the popular concept of tropical meteorology, where a parallel arrangement with respect to the geographical equator is assumed, on the basis of the latitudinal migration of the zone of maximum insolation. There seems no reason to doubt that the presence in the tropical West Pacific of such an asymmetrical pattern is due to the contrasting effects on the general circulation of the enormous heat-engine of the Australian continent, the major meteorological barrier of the 1,500 mile long cordillera of New Guinea and the vast water surface of the Pacific.

Further evidence of asymmetry is found in the distribution of areas experiencing a prominant double maximum in rainfall. Of the considerable area of northwest New Guinea lying virtually on the equator, only the eastern part of the islands in Geelvink Bay and the Cap d'Urville experiences a strong double crest (Fig. 3). Similar occurrences on Manus Island and in the vicinity of Rabaul could be an east-southeast extension of the double maximum belt, but by far the largest extent of this type of rainfall seasonality is in the southern part of the New Guinea cordillera. Further isolated anomalies of double maximum appear in the eastern islands of Milne Bay and a small area of the western Solomons.

The occurrence of a belt of double maximum confined to the mountains at about lat. 6° S coincides with an area of extremely low total variance. LANDSBERG (1951), in his studies of the island of Oahu, Hawaii, has found a similar low variance, relative to the coastal areas, and suggests that the topographic influences of tropical mountain regions are often strong enough to override small changes in the general circulation to which coastal climates are highly sensitive. The independent climate of the New Guinea highlands could be due to a similarity of air masses throughout the year. The enforced uplift and stagnation of the relatively dry southeasterlies against the 8,000–12,000 feet barrier of the southern face of the cordillera in the low-sun period results in moisture and instability characteristics more akin to those of equatorial air masses which lie over the area for the rest of the year, than to those of the free-flowing air of the southeasterlies.

The incidence of anomalous dry areas within this region of generally very high rainfall deserves detailed study, for although these areas are small in extent, their economic potential is considerably higher than surrounding areas. The north coast of New Guinea and associated inland areas are of particular significance in this context, the main anomalous areas being Waigeo Island, the Wewak district, the inland New Guinea dry zone, and Rabaul. Though this region seems to lie beyond the effective influence of the southeasterly air stream it must experience easterly winds in certain sectors of the vortical circulations and prolonged periods of these winds could cause extremely dry weather. Even in those areas south of the cordillera where the southeasterlies are dominant, there are intriguing problems such as the central Papuan dry zone and the wider range of seasonal variation in the eastern than in the western Solomons.

Probably the most complex problem to arise from this study is the relationship between the climate of the mountainous areas and the general circulation. Scarcity of rainfall data has necessitated large generalisations when mapping climatic features of these areas which by virtue of their highly complex local topography must posses a high degree of climatic variation over relatively small distances.

The effect of slope and altitude on rainfall is only imperfectly understood, for there is nowhere any line of stations placed at equal intervals of altitude up a mountain slope. BECKINSDALE (1957) suggests that as in temperate latitudes an increase of rainfall of four inches for every hundred feet of ascent can be expected up to a critical level. MOHR (1933) suggests that in Indonesia this zone of maximum rainfall occurs around 5,000 feet, and from observation of vegetation there is some evidence that this generalisation holds true for the outer ranges of the New Guinea cordillera. Within the ranges, however, it certainly lies several thousand feet higher; but as no station lies above 6,800 feet, and only a few isolated stations lie above 5,000 feet, the presumably drier summits of the higher mountains cannot be mapped with accuracy and are therefore excluded from Fig. 1.

Our discussion of the controls of seasonality, and of the geographical distribution of seasonal regimes is based on data which are far from adequate. With the addition of new data, concepts of the general circulation within the tropics may undergo radical change. The results of this application of harmonic analysis have shed light on many problems of the area, and we hope they may provide clues and incentive to understand more fully the climatology of this and other tropical maritime regions.

References

ASHTON, H. T., 1946: The principles of forecasting over the equatorial area north of Australia. Weather Development Research Bulletin, No. 7 Commonwealth Bureau of Meteorology, Australia.

BECKINSDALE, R. P., 1957: The nature of tropical rainfall. Trop. Agric. (Trinidad). 34, 76–98.

BRAAK, C., 1921-9: Het klimaat van Nederlandsche-Indie. Koninklijk Magnetisch en Meteorologisch Observatorium te Batavia.
BROOKFIELD, H. C., 1965: Natural Resources. In E. K. Fisk ed., New Guinea on the Threshold. Canberra, Australian National University.
BROOKS, C. E. P. and CARRUTHERS, N., 1953: Handbook of Statistical Methods in Meteorology, London, H. M. S. O.
BUDYKO, M., 1956: Teplovoi balans zemnoi pover khnosti. Gidrometeorologichekoe izdatel'stvo, Leningrad. (English translation: N. A. Stepanova, The heat balance of the earth's surface. Office of Technical Services, U. S. Department of Commerce, Washington, 1958.
CONRAD, V. and POLLAK, K. L. W., 1951: Methods in Climatology. Cambridge, Mass. Harvard University Press.
CURRY, L. and ARMSTRONG, R. W., 1959: Atmospheric circulation of the tropical Pacific Ocean. Geographiska Annaler. 41, 245–255.
FITZPATRICK, E. A., 1964: Seasonal distribution of rainfall in Australia analysed by Fourier methods. Archiv für Meteorologie Geophysik und Bioklimatologie. 13, 270–285.
GIOVANELLI, J., 1952: Les Cyclones Tropicaux en Nouvelle – Calédonie au cours d'un siècle, (1852–1952). Noumea, Service Météorologique, Publication No. 2.
HORN, L. H. and BRYSON, R. A., 1960: Harmonic analysis of the annual march of precipitation over the United States. Annals Assoc. of Amer. Geogr. 50, 157–171.
HOUNAM, C. E., 1951: Meteorological and climatic conditions over British New Guinea and adjacent islands. In: Resources of the Territory of Papua – New Guinea. Vol. 1 Ch. 3, pp. 34–54. Government Printer, Melbourne.
KARELSKY, S., 1956: Classification of the surface circulation in the Australasian region. Meteorological study No. 8, Commonwealth Bureau of Meteorological, Australia.
LANDSBERG, H., 1951: Statistical investigations into the climatology of the island of Oahu. Meteorol. Monog. 1, 3, 7–23.
MALKUS, J., 1955: The effect of a large island upon the trade-wind air stream. Quart. J. Roy. Meteorol. Soc. 81, 538–550.
MERRIT, E. S., 1964: Easterly waves and perturbations, a reappraisal. J. Appl. Meteorol 3, 367–382.
MOHR, E. C., 1933-38: De bodem der tropen in het algemeen, en die van Nederlandsche-Indie in het bijzonder. Meded. Kon. Inst. v. d. Trop., Amsterdam (translated by R. L. Pendleton (1944): Soils of Equatorial Regions. Michigan, J. W. Edwards, Ann Arbor.
Naval Intelligence Division Pacific Islands, 1945: Vol. 4, Western Pacific. London, H. M. S. O.
PALMER, C. E., 1951: Tropical Meteorology. In: Compendium of Meteorology, ed. T. F. Malone (American Meteorological Society) pp. 859–880 Waverly Press Inc. Baltimore.
SABAGH, M. A. and BRYSON, R. A., 1962: Aspects of the precipitation climatology of Canada as investigated by the method of harmonic analysis. Annals Assoc. Amer. Geogr. 52, 426–440.
THOMPSON, B. W. 1951: On the general circulation of the atmospere over S. E. Asia and the western Pacific. Quart. J. Roy. Meteorol. Soc. 77, 569–597.

JUNGE LAUFÄNDERUNGEN DES DESAGUADERO UND DIE ENTSTEHUNG DES URU-URU-SEES (BOLIVIANISCHER ALTIPLANO)

Ein Beitrag zur klimabedingten Morphogenese eines Endseebeckens [1])

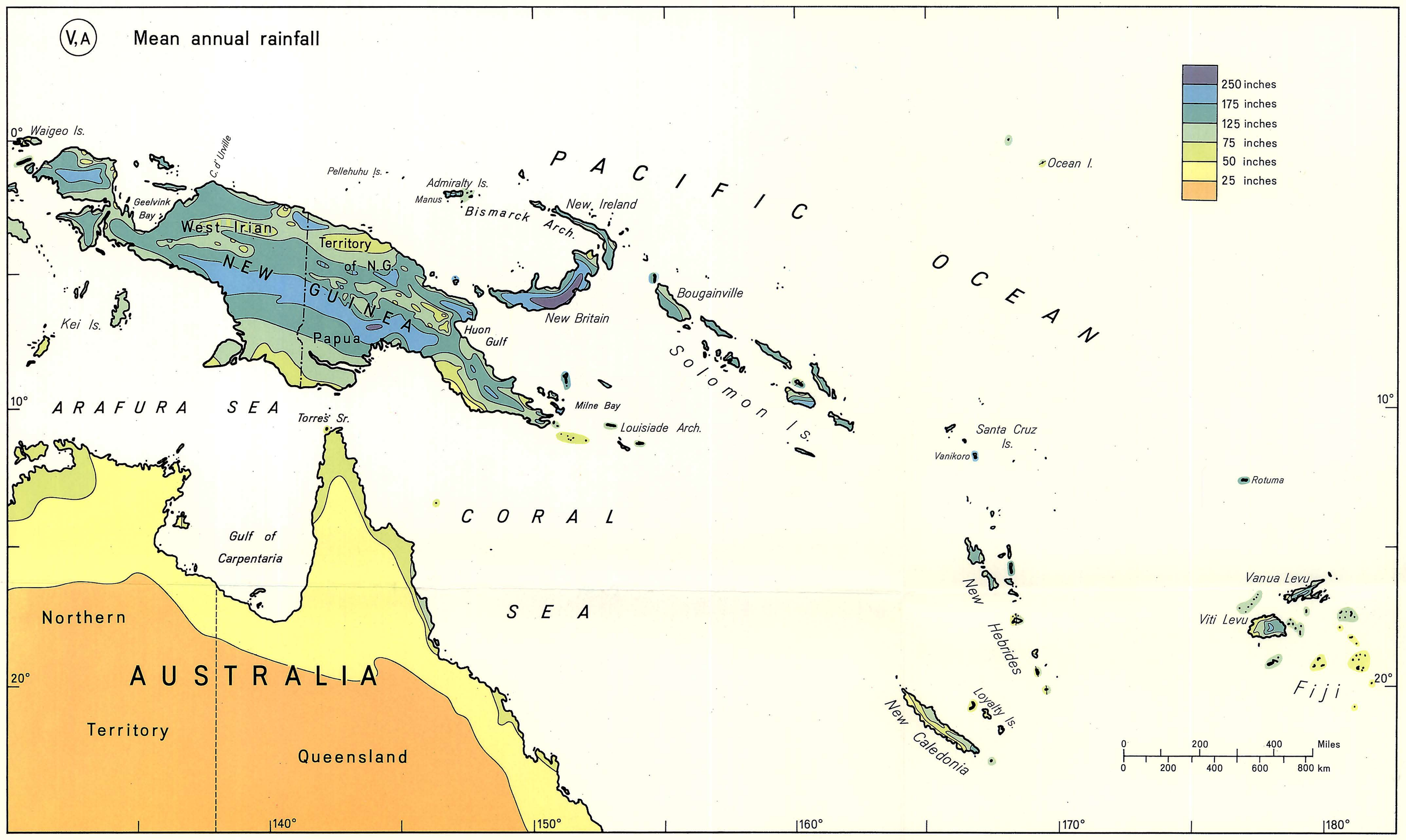
Mit 4 Abbildungen und 6 Bildern

ALBRECHT KESSLER

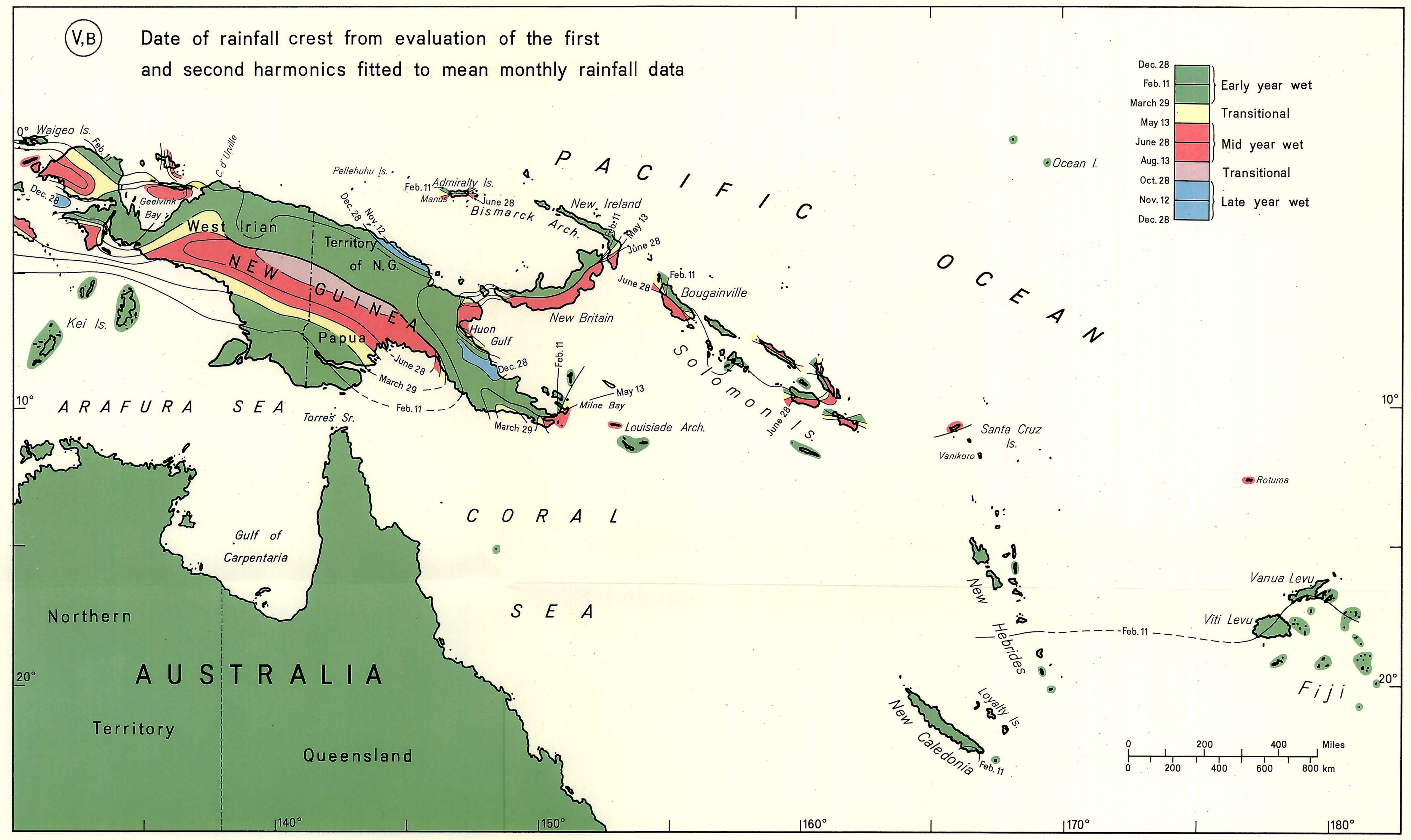
Summary: Recent changes in the course of the Desaguadero and the origin of Lake Uru-Uru (Bolivian Altiplano).
The lower course of the Desaguadero has experienced marked changes in the last 40 years. In the same period a new lake has appeared which has developed into a stream source. The origins and reasons are illustrated. The morphological situation was the subdued relief of an old sea floor with flat, sunken depressions, formed by the lower Desaguadero as a bank-full stream. An analysis of the water budget of the Desaguadero is presented. Large fluctuations in runoff periodically alter the transporting power of the river, resulting in considerable erosion of the bed and sediment deposition. Several changes in river course have occurred at periods of summer maximum flow and these always orient themselves to the left bank, probably in accordance with the Coriolis effect. The sequence of development of the ice-age Lake Minchin and its effect through the recent course changes of the Desaguadero on the formation of Lake Uru-Uru is compared to similar relationships in the Tarim Basin and the similar result of these climatically conditioned morphogeneses explained.

Die bolivianische Minenstadt Oruro sieht sich heute einer seltsamen Situation gegenüber. Während Geologen wegen des steigenden Trinkwasserbedarfs der Stadt unter Schwierigkeiten neue Quellen erschließen müssen, schiebt ein jüngst entstandener See seine Ufer langsam gegen die südliche Stadtgrenze vor. Der Panamerican Highway La Paz – Oruro – Uyuni, eine befestigte Schotterpiste, ist bereits zwischen Oruro und Machacamarca von den Fluten überspült (Bild 1). Der Autoverkehr umgeht den See im Osten in zahllosen, täglich neu entstehenden Spuren, deren Liniengewirr die Tonebenen durchkreuzen. Der Bahnkörper der Strecke La Paz – Potosi muß dauernd mit Steinen befestigt werden, um dem nagenden Wellenschlag des neuen Sees wenigstens noch

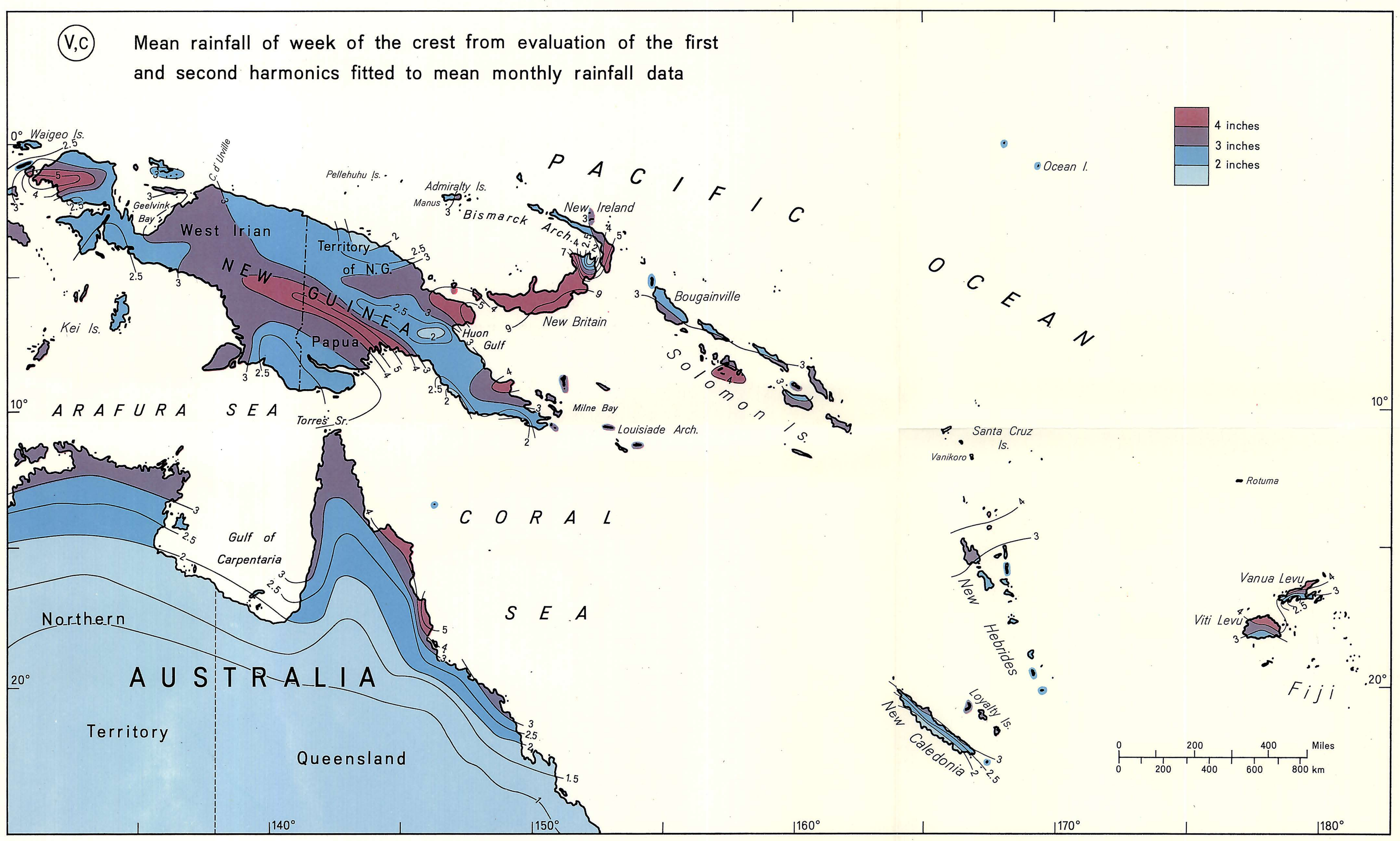
1) Für mündliche Auskünfte habe ich den Herren RÜDE und KIERIG (Oruro), Dr. THORMANN und Ing. URQUIDI (La Paz) zu danken. Herr Ing. URQUIDI machte mir außerdem dankenswerterweise einen Plan des Uru-Uru-Sees zugänglich.



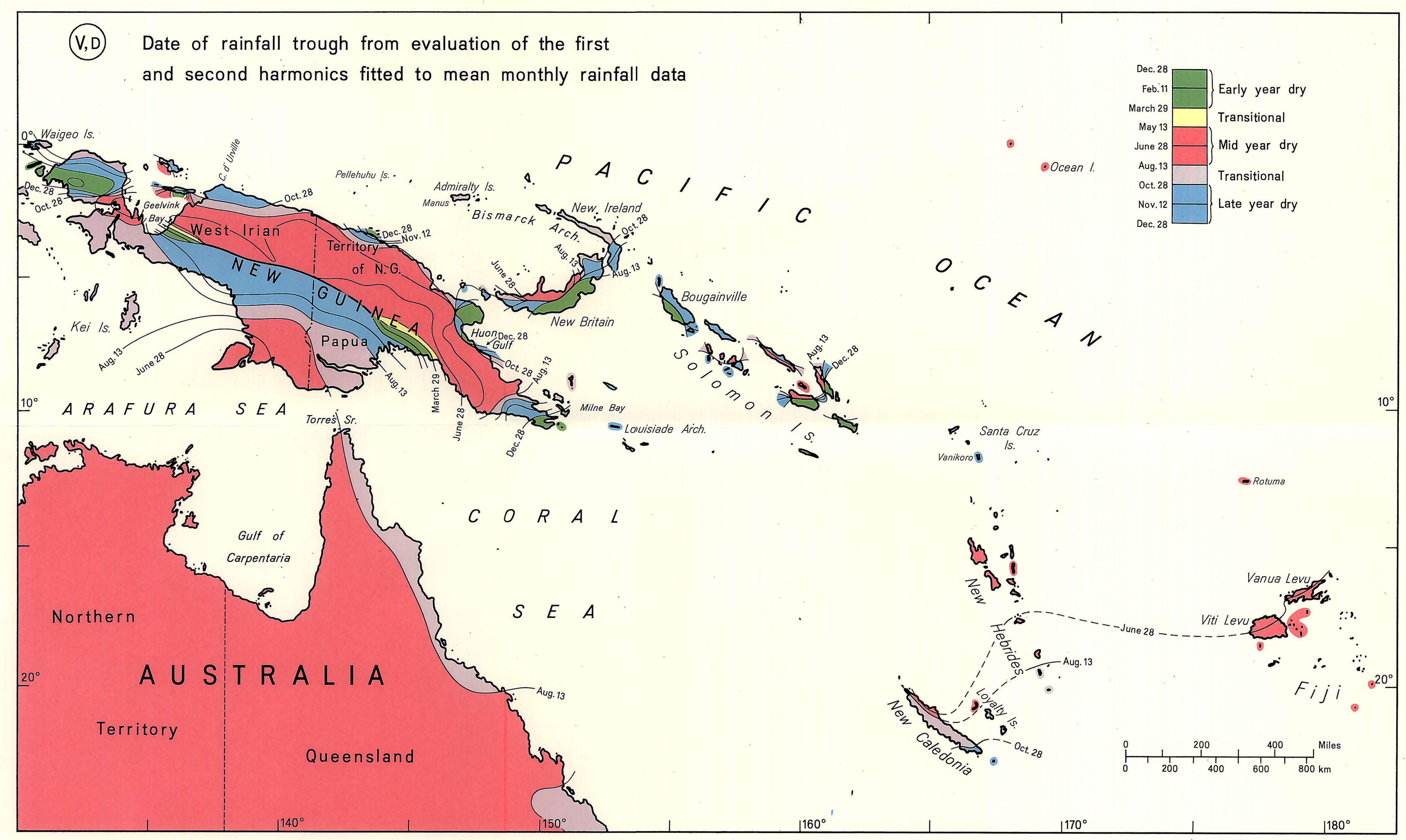
Mean annual rainfall



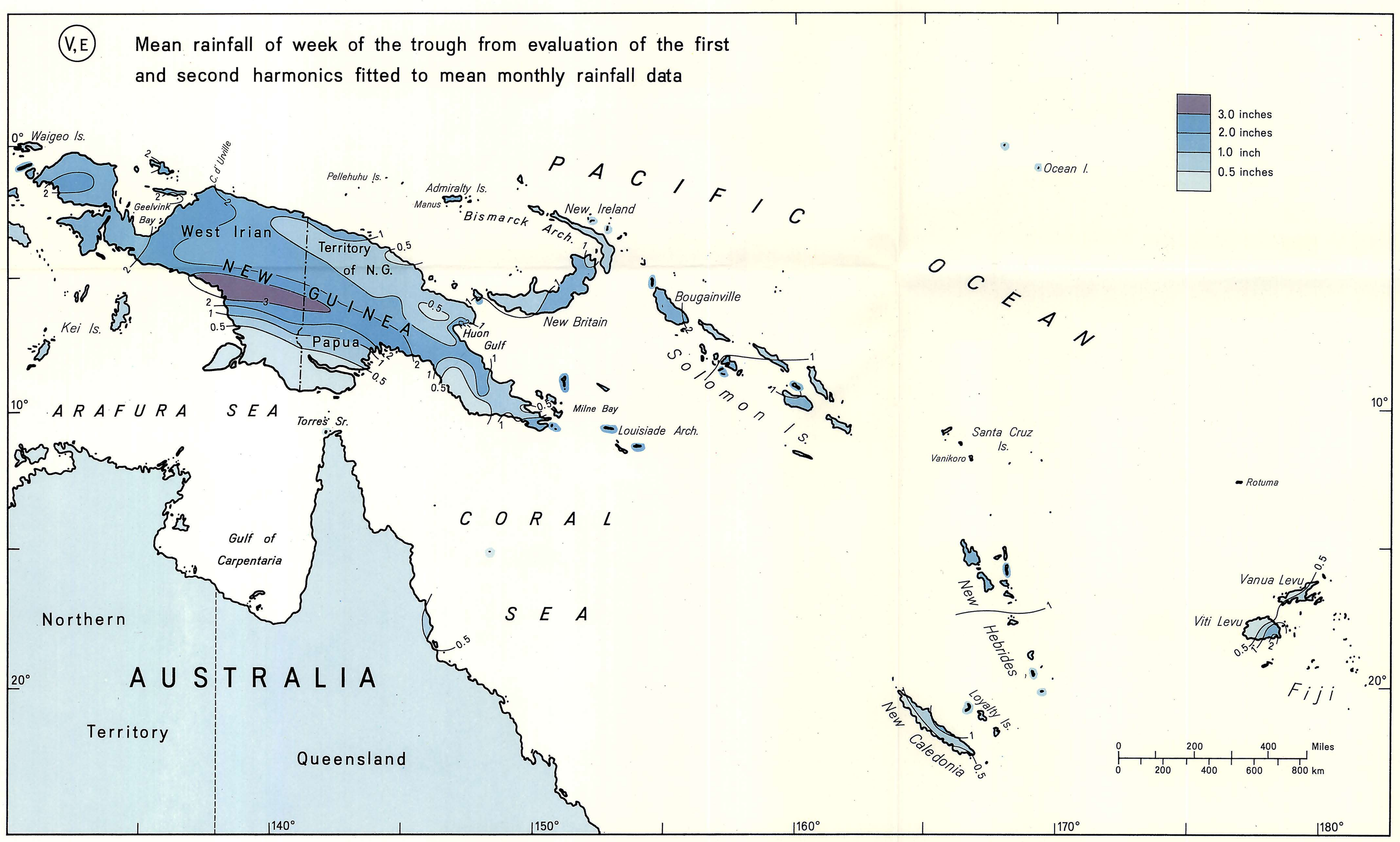
Date of rainfall crest from evaluation of the first and second harmonics fitted to mean monthly rainfall data



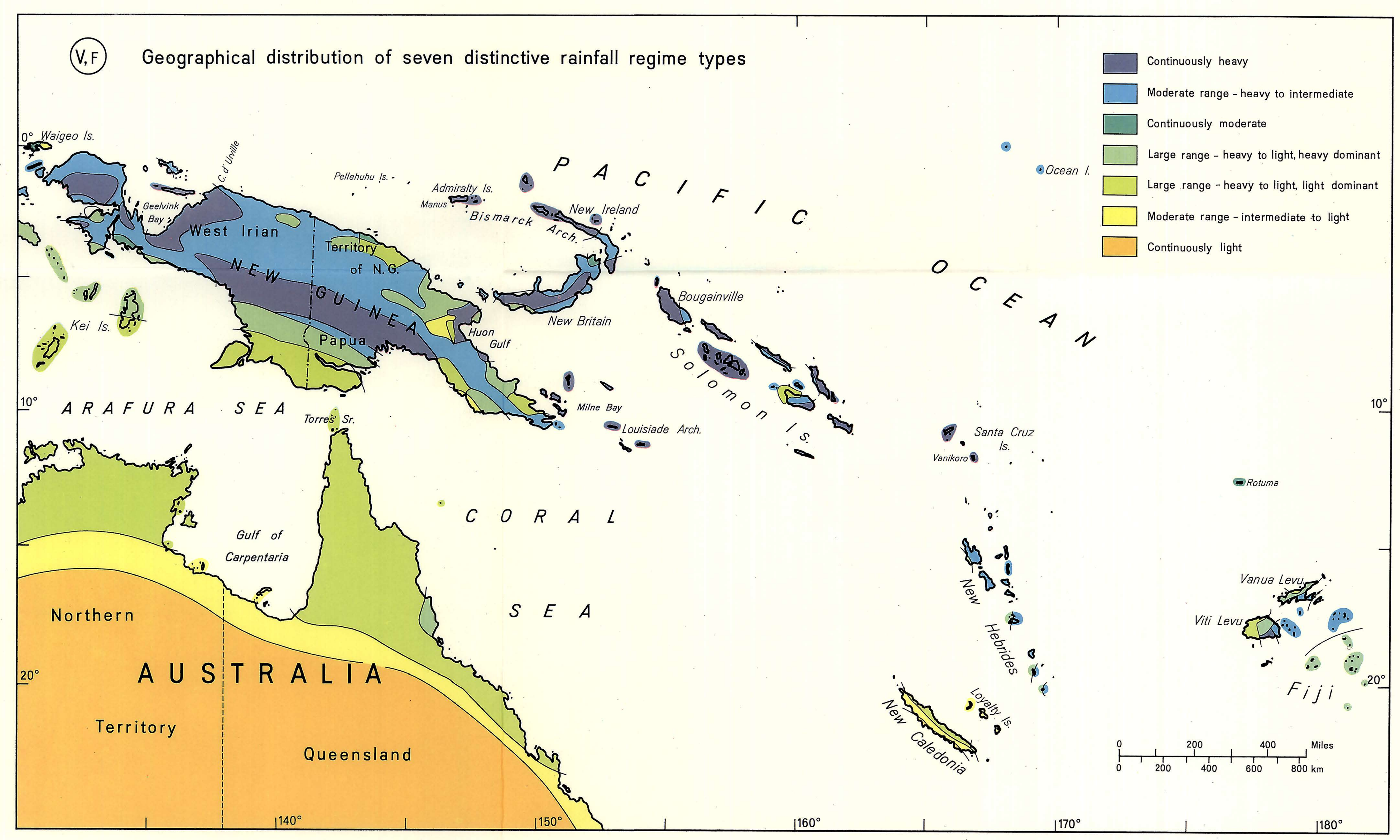
Mean rainfall of week of the crest from evaluation of the first and second harmonics fitted to mean monthly rainfall data



Date of rainfall trough from evaluation of the first and second harmonics fitted to mean monthly rainfall data



Mean rainfall of week of the trough from evaluation of the first and second harmonics fitted to mean monthly rainfall data



Geographical distribution of seven distinctive rainfall regime types

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