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ON RAINFALL VARIATIONS IN NEW ZEALAND

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Introduction

At last year's ANZAAS conference in Melbourne, drought was the main subject of at least one paper. In several others the effects on plants of water shortages during periods of low rainfall were discussed. Drought was then, as now, a matter of great concern in Australia. In parts of the southeast, unusually deficient rainfall for several years has had serious economic consequences.

In New Zealand too, droughts and dry spells are important in the consideration of water resources, although on a shorter time scale. Here, except in the limited areas of lowest average rainfall, yearly rainfall totals are seldom much less than the annual water needs of vegetation. Thus in New Zealand, for the most part, the dry periods of economic consequence for agriculture or engineering have durations of a few weeks or a few months.

Most rain in New Zealand is associated with relatively large scale weather systems - depressions or frontal low pressure troughs which characteristically give one or more days of rain over large parts of the country. The intervening high pressure systems usually give several days without much rain. The obvious coherence in rainfall distribution associated with these moving systems is reflected in the statistical persistence found in daily rainfalls (see Finkelstein 1967). Dry and wet spells of longer duration appear to arise virtually at random, although Seelye (1946) demonstrated a small degree of persistence in monthly rainfall. (The probability of a drier than average month following a dry month was 0.59). During a typical drought the troughs and centres of low pressure are weak, or pass far from the areas concerned, and they come between persistent strong anticyclones. Thus apparently by chance a season occasionally occurs with very persistent or very widespread low rainfall. Such a season was experienced, for example, in 1963-64 when "drought disaster" was officially declared in a number of districts from Northland to Otago (Table 1), lasting from spring 1963 in some areas through the winter and spring of 1964 in others. (Fig. 1).

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Table 1

Districts and seasons in which 'Drought Disaster' was declared, 1963-1964

District	Season
Northland	Spring (1963), Summer, Autumn, Winter
Thames (Auckland)	Summer, Autumn
Rotorua-Bay of Plenty-Taupo	Spring (1963), Summer
Wairoa (East Coast, N.I.)	Summer, Autumn, Winter
Hawkes Bay	Summer
Wairarapa	Summer
Ashburton County (Canterbury)	Autumn, Winter
Mackenzie Country (Canterbury)	Summer, Autumn, Winter
North - Central Otago	Winter, Spring (1964)

Rainfall records from a large number of stations in New Zealand are available for water resource studies. In the Meteorological Service recent work on rainfall has been concerned firstly with the distribution of seasonal rainfall over New Zealand, and secondly with the space relations of rainfall, on a monthly, seasonal and annual basis.

The first of these topics was chosen partly because the season of three calendar months is the order of duration of many of the major recorded droughts and the great mass of rainfall data is as yet available for electronic processing only as monthly totals. It was considered useful to prepare maps of average seasonal rainfall, and to determine the variability, and examine the frequency distributions of seasonal rainfall. This work is to be reported in more detail (Coulter and Finkelstein, in preparation), but some results are briefly outlined below.

The second is an attempted step for answering the questions: How extensive are New Zealand droughts? If one district has a drought of specified severity, which other districts are likely to be affected, and which are likely to be having a wet or a normal season? If

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quantitative answers to such questions can be found they should have implications for economic planning, e.g. concerning stock movements and feed reserves required for optimum agricultural production.

Seasonal Rainfall Distribution

The distribution of rainfall totals in the calendar seasons (Summer: Dec. Jan. Feb.) have been studied to supplement previous work on monthly and annual rainfall. It may be desirable in future to extend to other groupings of months as well as to work with shorter time intervals. However, the seasons are for some purposes a convenient unit, and they are commonly used for comparisons.

The geographical distribution of average rainfall in New Zealand is well known, e.g. Fig. 2(a) shows average summer rainfall totals. These vary from more than 60 in. in Fiordland and the Alps to less than 5 in. in Central Otago. They are less than 10 in. in most of Southland, Otago, Canterbury, Marlborough, the Wellington Province and Hawkes Bay, and in areas near Gisborne, Hamilton and Auckland. As the potential evapotranspiration total for summer is approximately 10-11 in. in most of these areas, an average summer rainfall, even if well distributed over the season, will provide less than full plant water needs, and little or no water will be available for runoff. Even a relatively small rainfall deficiency can then have significant effects on agricultural production.

Somewhat similar patterns of average rainfall are found in the other seasons. Figures 2(b) and 2(c) show the season of highest and lowest average rainfall, with the relevant percentage of the annual total shown where this exceeds 30 per cent or is less than 20 per cent. No season anywhere gets very much more or less than a quarter of the annual rainfall on average. Some extremes are:

16% in Central Otago in winter;

more than 30% in the north and east of the North Island and in Banks Peninsula in winter;

more than 30% in Central and North Otago in summer.

Winter rainfall predominates in the North Island and in the north of the South Island and about Banks Peninsula. In the remainder of the South Island summer or autumn rainfall predominates. (At many of the stations used in preparing these maps, 35 to 50 years of record were available. Another sample of similar length would not give precisely the same values. The probable sampling errors will be

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discussed in the paper on Seasonal Rainfall).

The standard deviation of the seasonal rainfalls gives a measure of the scatter in individual seasonal totals. (Its value tends to be greatest where the average is greatest). The ratio of standard deviation to the mean or coefficient of variation (v) is shown in Fig. 3 for summer and winter. It is generally greatest in the east of the country (and in the north in summer) exceeding 0.5 in a few places; and lowest in the south and west where it is often less than 0.2. There are seasonal differences. Except in Otago, spring and winter have generally the lowest values. This distribution is broadly similar to that of monthly variability (Seelye 1940). For comparison, values of seasonal variability index (the ratio of the average of departures from the mean without regard to sign, to the mean) have a maximum of approximately 40 per cent in summer and autumn in Hawkes Bay and Northland, and a minimum of 15 to 17 per cent on the west coast of the South Island in winter and spring. The range in monthly variability is from 18 per cent at Puysegur Point in May to 77 per cent at Waimarama in Hawkes Bay in January.

Frequency Distribution of Seasonal Rainfall

Seasonal rainfall is not normally distributed, as the distributions are zero bounded but include occasional very large values. Histograms of the distributions at representative long period stations whose records are considered to be relatively reliable show a varying degree of positive skewness. They show also that even with 50-60 years of record there are large irregularities in the observed frequency distributions for a single station. The irregularities could be largely eliminated if the separate station data were combined into a single composite series, but this would obliterate any geographical differences which might exist.

Fitting of a theoretical curve has some value in that it can provide a compact representation of a large mass of data, and as it enables smoothed interpolations of quantile values to be made objectively. The theoretical "gamma" distribution (Thom 1958) has been found to give good fit to precipitation climatological series (Thom 1966). Applied to New Zealand seasonal rainfall series it appears to fit the actual distributions satisfactorily.

The gamma frequency distribution is defined by its probability density function

$$g(x) = \frac{1}{\beta^{\gamma}\,\Gamma(\gamma)}\, x^{\gamma-1} e^{-\frac{x}{\beta}}$$

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where β is a scale parameter, γ is a shape parameter and $\Gamma(\gamma)$ is the ordinary gamma function of γ.

Estimates of the parameters may be obtained as follows (Thom 1966):

$$\gamma = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \quad \text{and} \quad \beta = \frac{M}{\gamma}$$

where $A = \ln M - \Sigma \ln x / N$, M is the mean value of the variate x, and N the number of terms in the sample.

The distribution function $G(x) = \int_0^x g(t)dt$ Pearson's (1951) "Tables of the Incomplete -function" gives g (u,p) where $u = \frac{x}{\beta\sqrt{\gamma}}$ and $p = \gamma - 1$.

The gamma distribution is zero bounded. For $\gamma > 1$ it is bell shaped with mode at $\beta(\gamma-1)$. With increasing γ the distribution becomes more symmetrical and slowly approaches the normal distribution. If the variate is expressed in terms of the mean ($x' = x/M$), is unchanged and the mode becomes $1-1/\gamma$. In the gamma distribution the coefficient of variation (v) and the skewness parameter($\sqrt{G_1}$) are determined by the value of gamma as follows:

$$\sqrt{G_1} = 2V = 2/\sqrt{\gamma}$$

Two examples of observed and theoretical distributions, for Napier, summer, and Ross, spring, are illustrated in Fig. 4. They were chosen as representing near extremes in the character of the distributions. The histogram gives the observed frequencies, the solid line the theoretical gamma frequency curve fitted to the data. The curve for Napier is highly skew ($\gamma = 4$), that for Ross is more nearly symmetrical ($\gamma = 23$).

Fig. 5 gives the distribution function (cumulative probability curves) for selected values of γ for the variate x'. It may be used (by interpolating for γ) instead of the tables, from which it was constructed, to derive approximate values of the probability for the values of γ likely to be encountered with seasonal rainfalls in New Zealand.

Fig. 6 shows for summer and winter the distribution of the gamma parameter found for some 135 stations in New Zealand. Of these 66 had records of at least 50 years while most of the remainder were at least 30 years. The distribution of γ over the country shows, as expected, a rough correlation with the coefficient of variation. The isopleths have been smoothed to some extent, and as with other isopleths drawn on this scale they do not necessarily apply to areas of high elevation. The value of γ ranges from approximately 3.0 in a few places near Napier and East Cape in summer and autumn to more than 20 in western areas in winter and spring.

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With values of σ taken from these maps, and values of seasonal rainfall (from, for example, maps such as Fig. 3a, or from average monthly rainfall tabulations), approximate quantiles of seasonal rainfall can be derived. For example, at places where $\sigma = 9$, the 20-percentile value (that exceeded four years out of five) is 72 percent of the mean.

Space Correlations of Rainfall

The spatial relationships of rainfall in New Zealand are determined by the interaction of topography and the various weather systems experienced. They are complex and it is not obvious how they can be subjected to statistical analysis that will be sufficiently discriminating but not so elaborate as to be unmanageable or to reduce sample sizes to an unacceptable level.

Geographical patterns of rainfall anomalies found in individual months, are illustrated for three recent months in Fig. 7. October 1967 was a dry month in many places, especially in the north. The two driest areas, near Kaitaia and near Auckland, had less than 25 percent of the average rainfall for the month. The areas were about a hundred miles in extent, and about the same distance apart. November was wetter than average in most of the country especially in middle areas of the South Island where rainfall exceeded 400 percent of average. Again the major anomaly elements cover half an island or more, but some features are on a smaller scale. In December the North Island was again largely wet, and the South Island variable. Major anomalies again cover about half an island. Details of the patterns are quite irregular and there is little apparent consistency in them from month to month.

As a first step in the statistical analysis, to seek broad relationships and their extent, correlation coefficients (r) have been calculated between monthly, seasonal, and annual rainfalls at a number of reference stations and at selected stations, mostly in the same province as the reference station in question. Figs 8 and 9 show some of the results, for Auckland and Christchurch as reference stations. Separate maps are given for annual totals, summer, January, and July. In all correlations the number of pairs was at least 30 and in most cases was more than 50. The shaded area is for $r > 0.7$ thus including areas where at least half the variance was in common with the reference station. Hatching indicates schematically the areas where correlation coefficients were less than the limiting significant value (at $P = 0.05$). The inset diagram shows confidence limits of r for 50 pairs.

In brief, the main features of these maps are as follows:-

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The correlations fall off fairly rapidly with distance reaching 0.7 at distances of 15 to 140 miles from Auckland and of 20 to 100 miles from Christchurch.

The area of high correlation tends to be greatest for summer months, and lowest for winter months.

The isopleths of r are roughly elliptical, with long axis parallel to the axis of the country, i.e. NW-SE at Auckland, NE-SW at Christchurch. The ellipses are roughly 2-3 times as long as broad.

With a few exceptions neighbouring stations give similar correlations, and the isopleths of r form reasonably consistent patterns which are related to topography. Although statistical confidence limits are wide (e.g. for $N = 30$, $r = 70$, the limits are 0.55 and 0.83 for $P = 0.05$) it is unlikely that this consistency is merely due to chance. It is not implied, however, that another sample of years would give exactly the same pattern.

In some few cases, mostly with Christchurch as reference station, statistically significant negative correlations were found.

Conclusions

Water resources planning is likely to be more concerned with the incidence of water shortage in times of deficient rainfall than with the occurrence of a surplus over a period of a month or more. Although the natural sequence of rainfall is measurable on a time scale of days at most, and although significant agricultural water shortage can arise in a shorter time than a month, useful information can be derived from rainfall statistics for months or seasons. The characteristics of point rainfall in New Zealand are by now reasonably documented for most of the country, both as to average amounts (N.Z. Met. S. unpublished maps and tabulations) and as to the variability and probability levels (e.g. Seelye 1940, 1946) and also in relation to water needs of vegetation (e.g. Gabites 1956, Rickard 1960, Coulter 1966) chiefly for the month and longer groupings of months.

The associations from place to place of rainfall anomaly are less well known. The simple correlations between rainfall amounts now being evaluated provide some useful background for this problem. They also contain material for speculation on climatic differentiation within the country, and will need to be considered in terms of synoptic climatology. Further work on specific drought periods of the past record is clearly necessary, especially with regard to the area affected. If feasible it would be desirable to assess probabilities of drought for specified areas. Finally, one should mention the

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ultimate aim of long-term forecasting of rainfall anomalies in periods of a month or more. Although some hopeful signs are emerging from the theoretical study of the general atmospheric circulations in the light of improving global observations, there is as yet no indication that accurate long range forecasting will be realised in the very near future.

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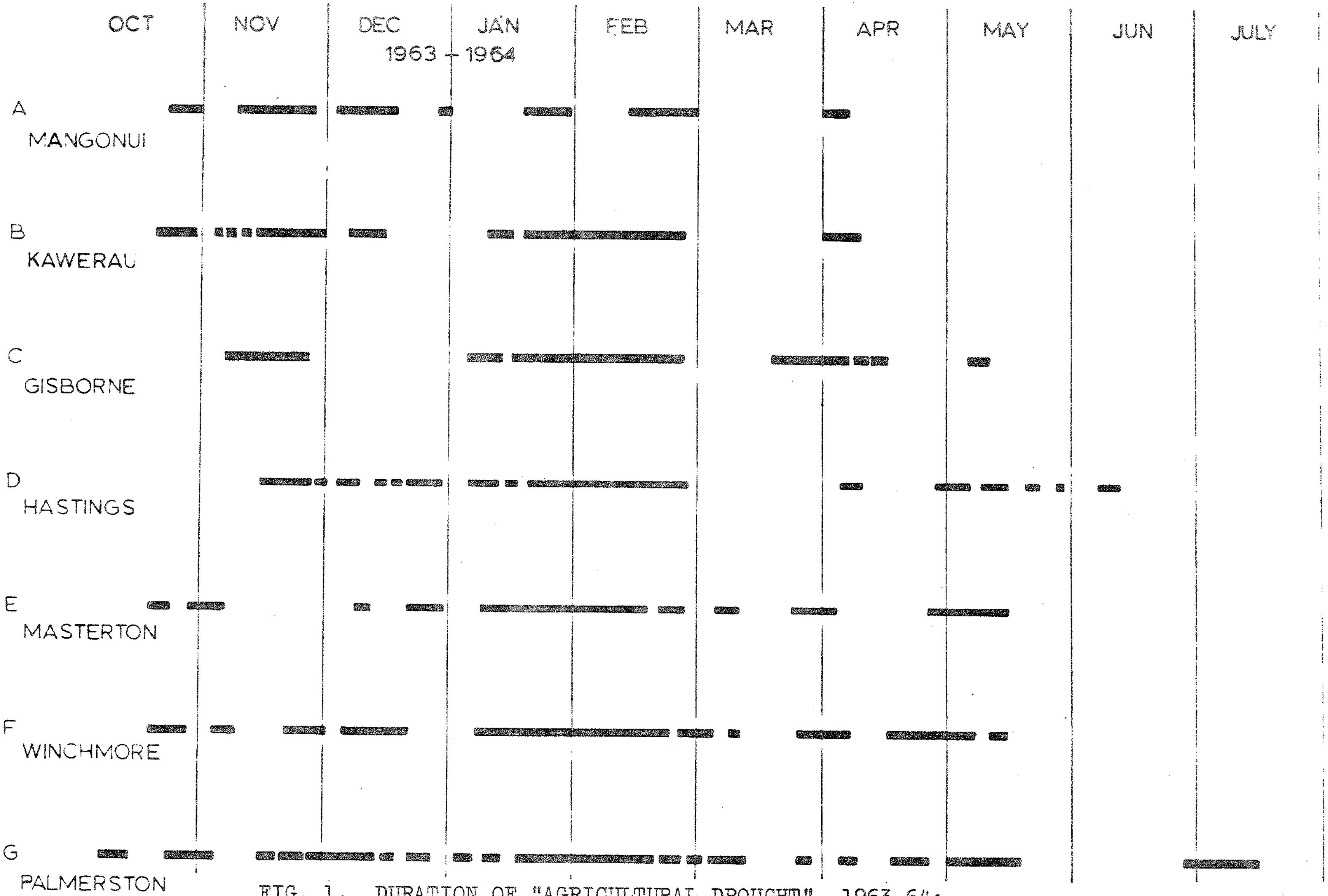

FIG. 1. DURATION OF "AGRICULTURAL DROUGHT", 1963-64: I.E. PERIODS WHEN SOIL MOISTURE WOULD HAVE BEEN DEPLETED BY 2 INCHES, ON THE BASIS OF REPORTED DAILY RAINFALLS AND TRANSPIRATION ASSUMED TO BE AT THE AVERAGE POTENTIAL RATE.

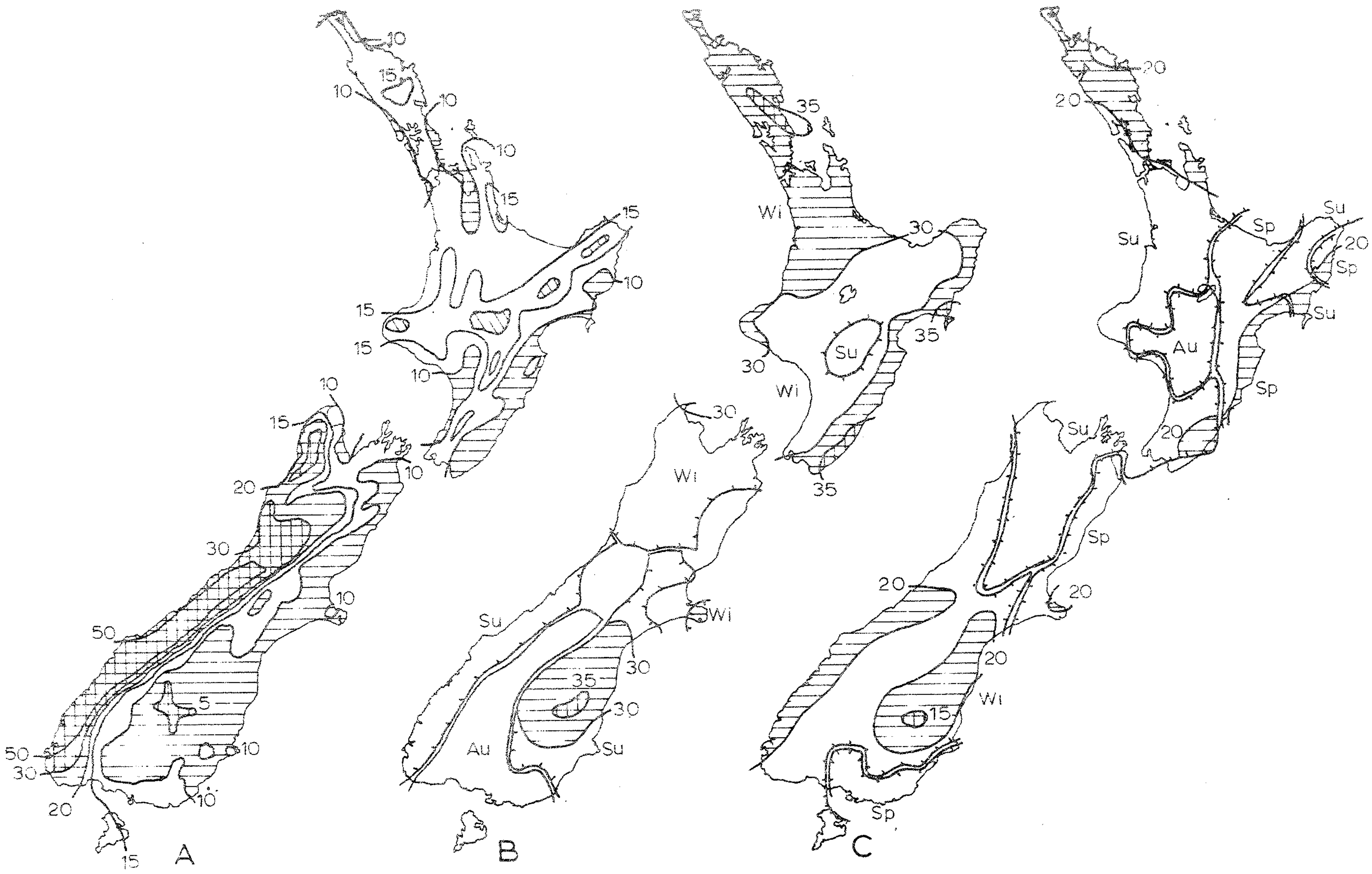

FIG. 2. SEASONAL RAINFALL:
(A) AVERAGE SUMMER RAINFALL (INCHES).
(B) SEASON OF HIGHEST AVERAGE RAINFALL, AND PERCENTAGE OF ANNUAL AVERAGE RAINFALL.
(C) SEASON OF LOWEST AVERAGE RAINFALL, AND PERCENTAGE OF ANNUAL AVERAGE RAINFALL.

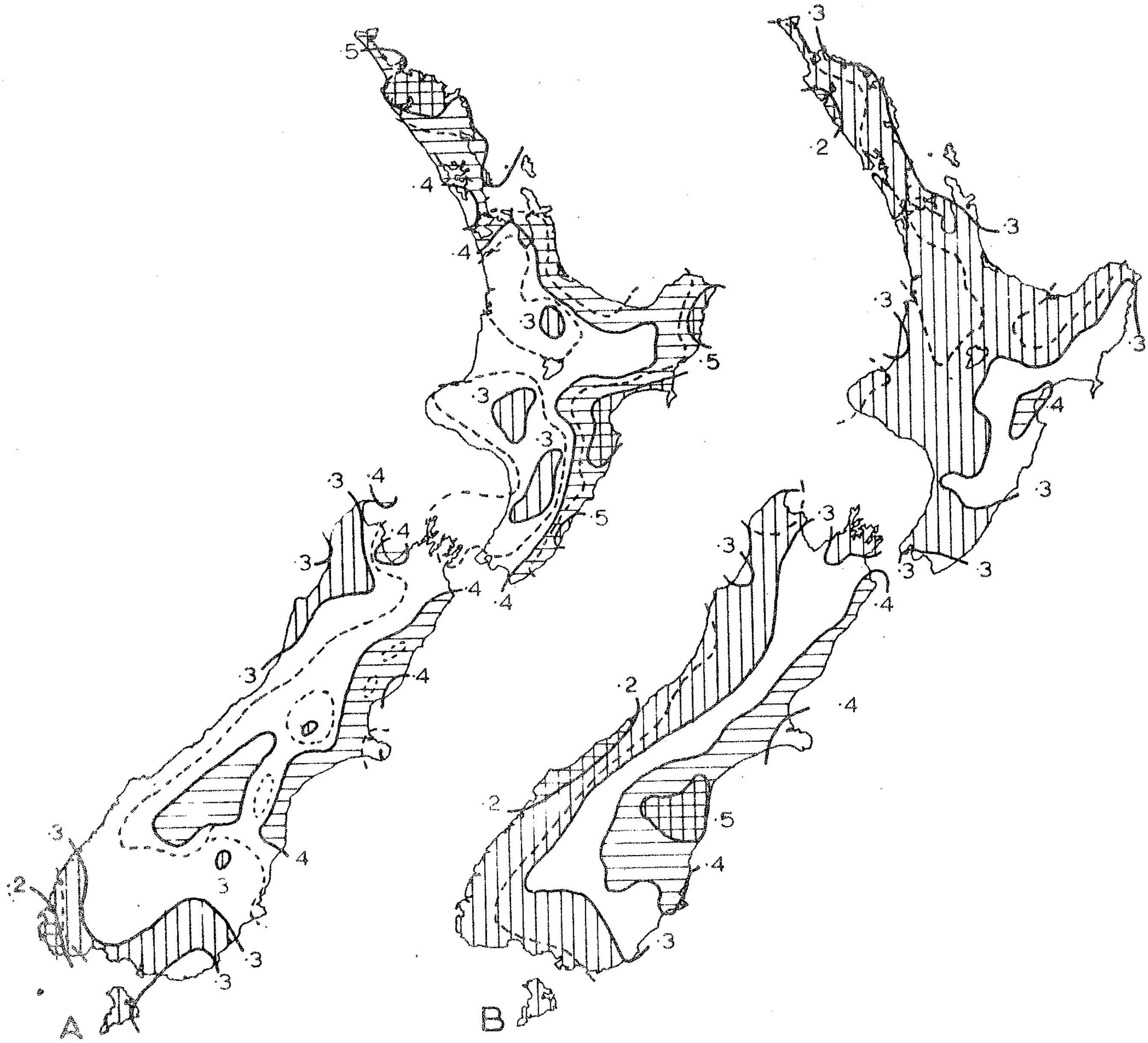

FIG. 3. COEFFICIENT OF VARIATION OF SEASONAL RAINFALL (S.D./MEAN):
A SUMMER B WINTER

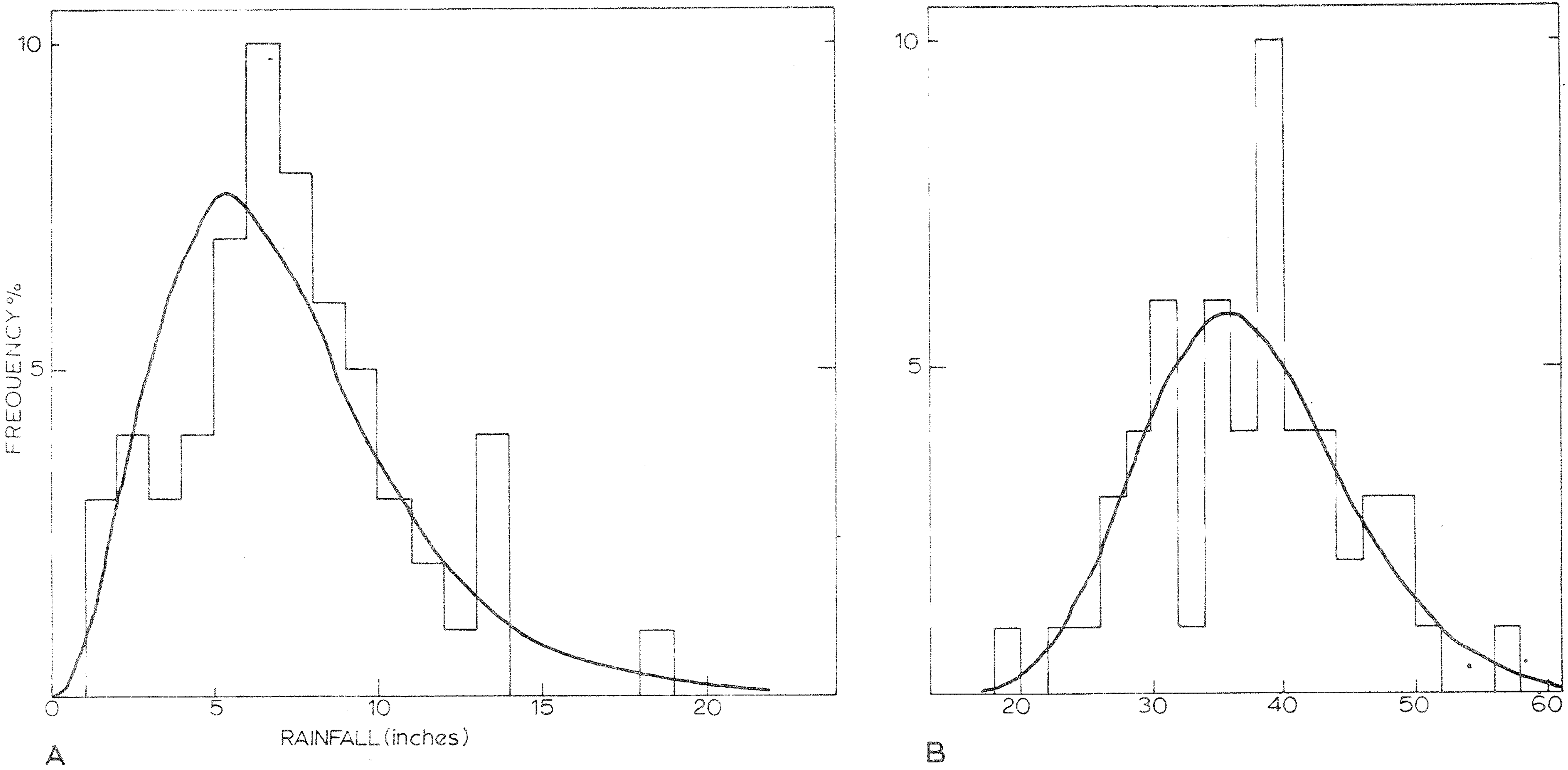

FIG. 4. HISTOGRAMS AND THEORETICAL "GAMMA" FREQUENCY CURVES
A NAPIER, SUMMER B ROSS, SPRING
(1900-1965; $\gamma = 4$) (1909-1965; $\gamma = 23$).

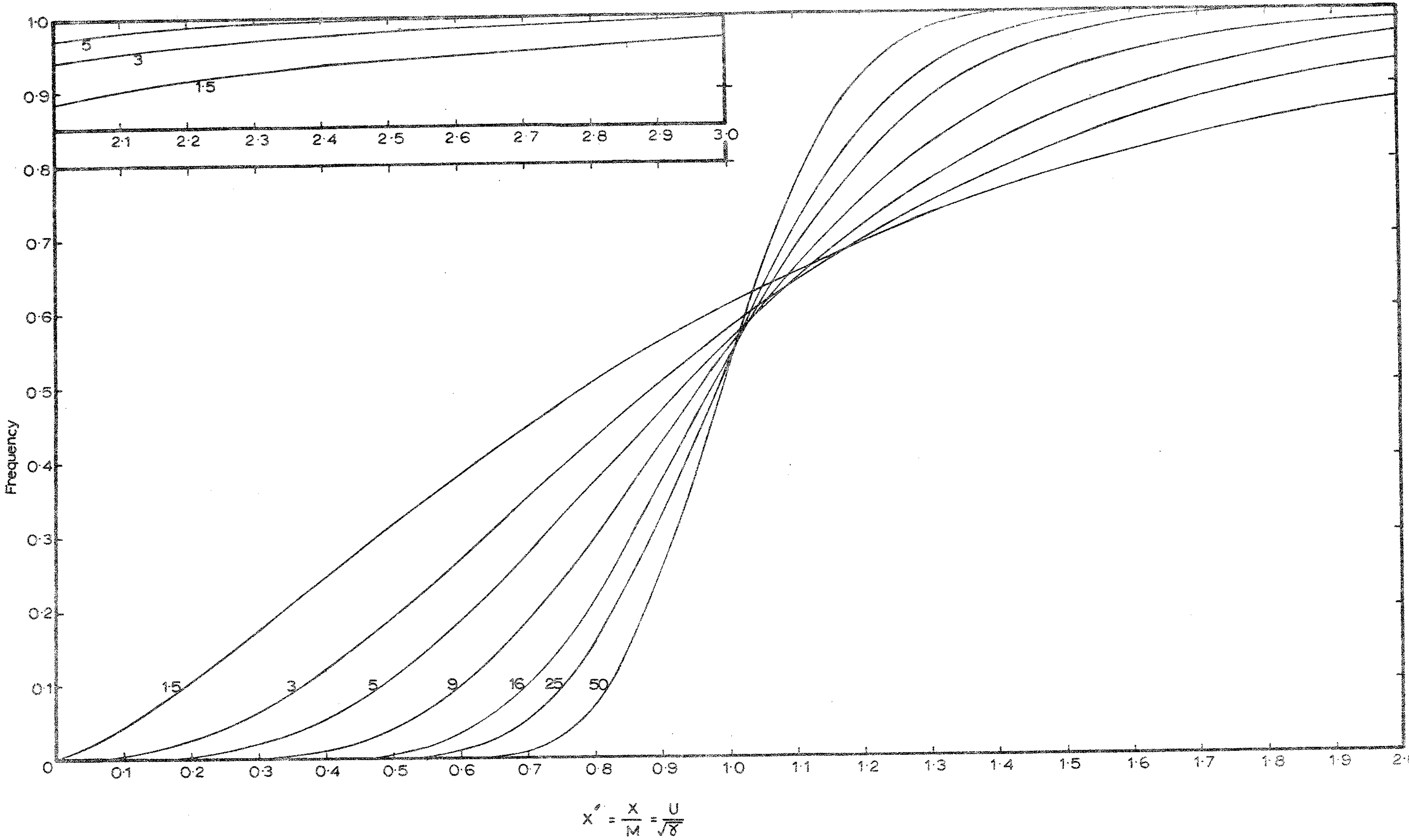

FIG. 5. GAMMA DISTRIBUTION CUMULATIVE PROBABILITY CURVES,
(FOR γ = 1.5, 3, 5, 9, 16, 25. 50).

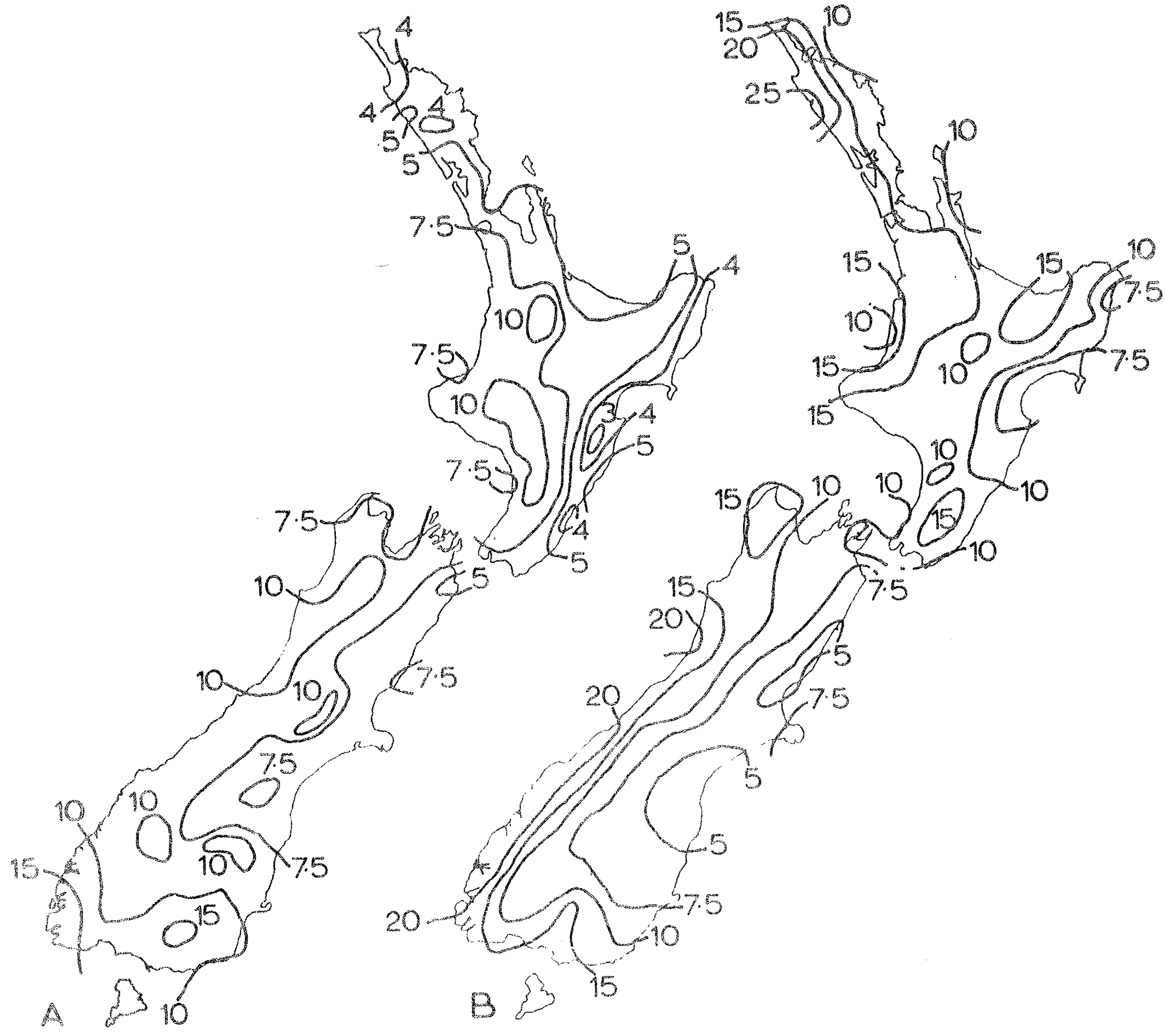

FIG. 6. DISTRIBUTION OF GAMMA PARAMETER (γ) IN NEW ZEALAND:
A SUMMER B WINTER

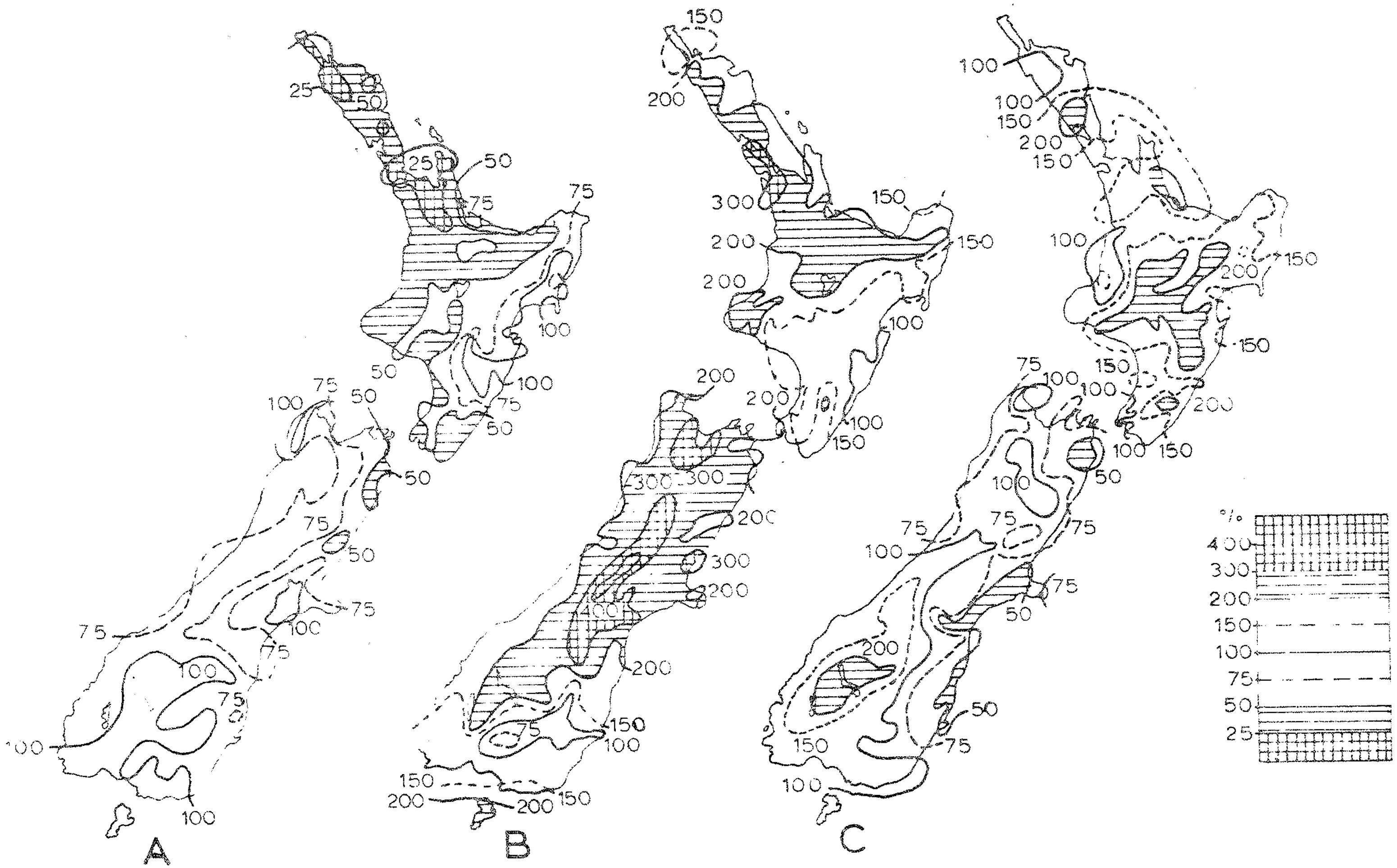

FIG. 7. MONTHLY RAINFALL ANOMALIES (PERCENTAGE OF NORMAL):
A OCTOBER, B NOVEMBER, C DECEMBER; 1967.

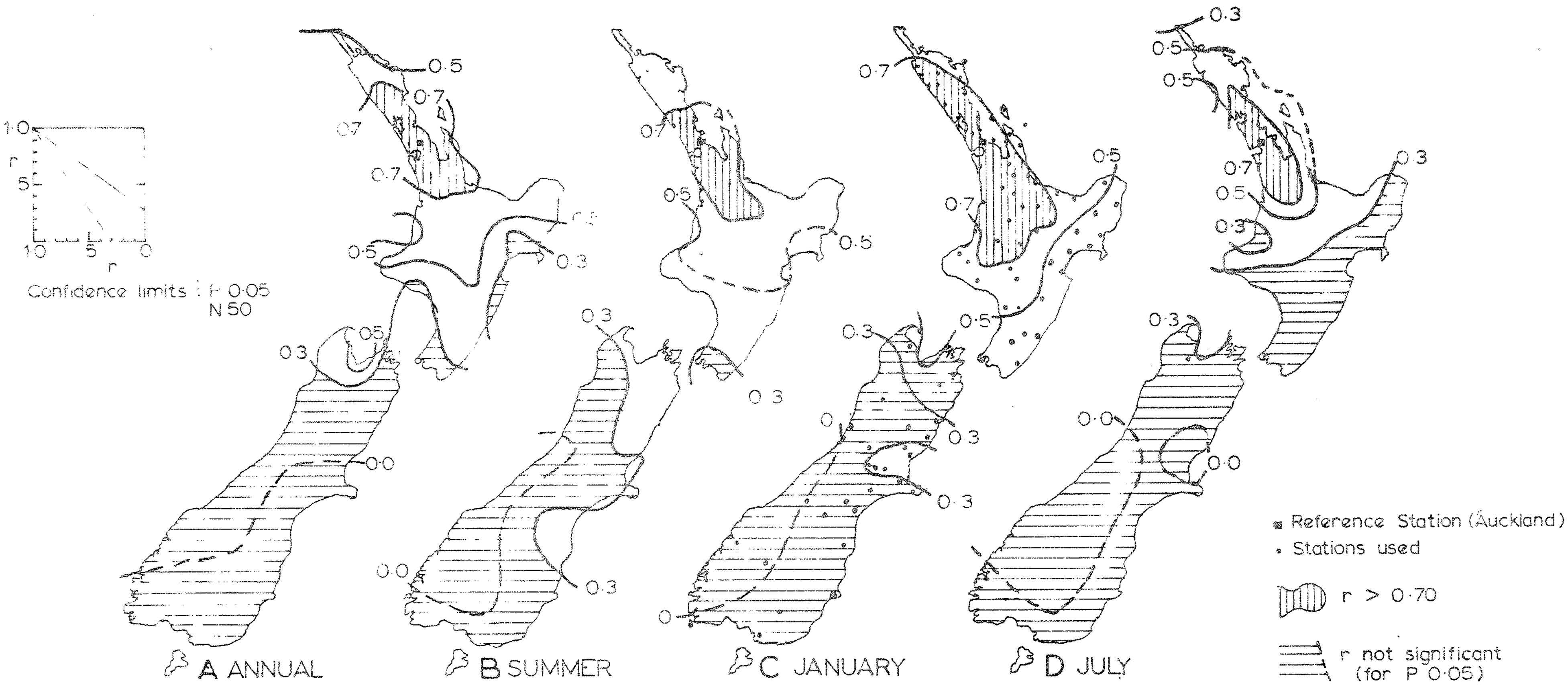

FIG. 8. ISOPLETHS OF CORRELATION COEFFICIENT WITH REFERENCE STATION AUCKLAND FOR
A ANNUAL, B SUMMER, C JANUARY, D JULY RAINFALL TOTALS.

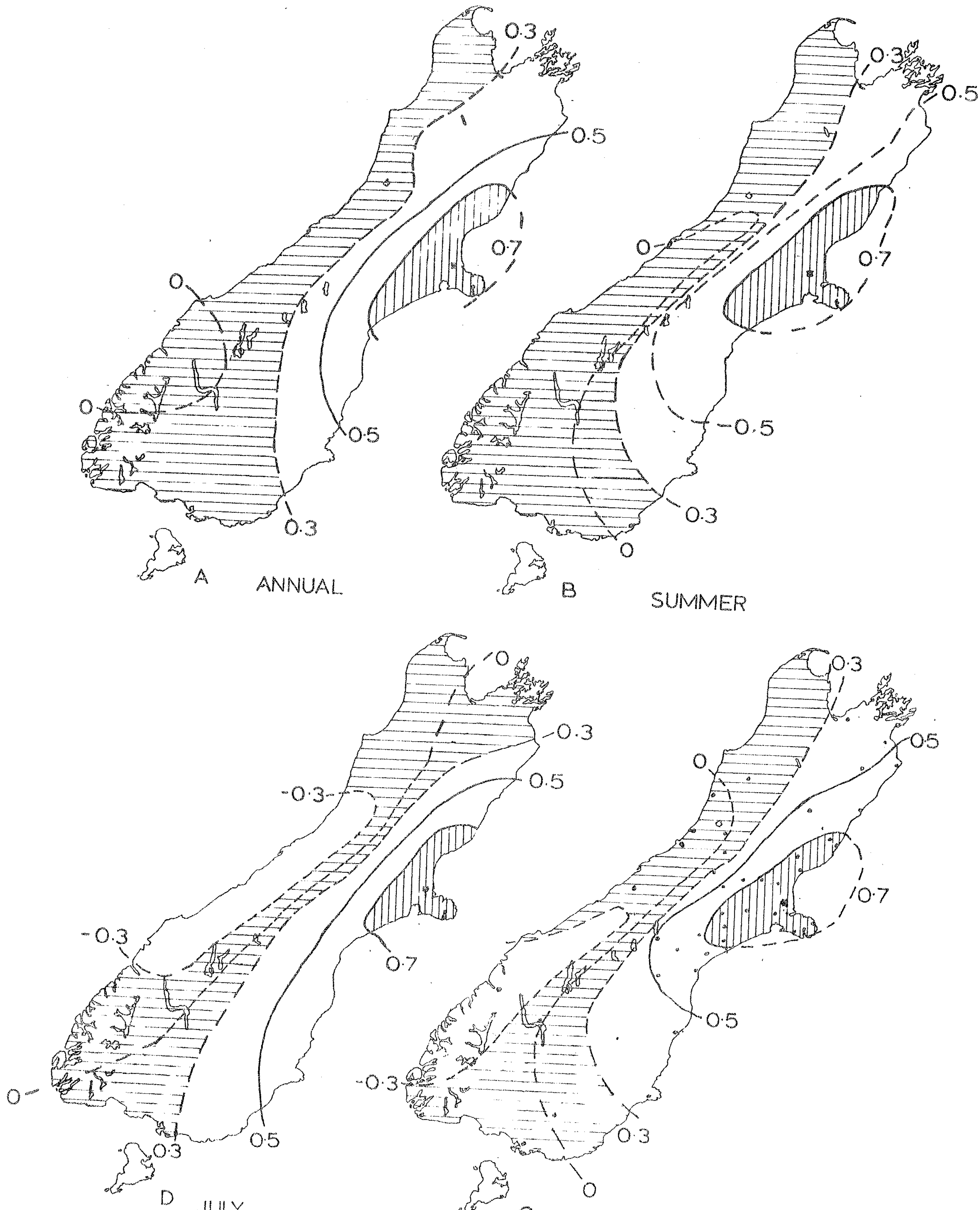

FIG. 9. ISOPLETHS OF CORRELATION COEFFICIENTS WITH REFERENCE STATION CHRISTCHURCH FOR A ANNUAL, B SUMMER, C JANUARY, D JULY RAINFALL TOTALS.
(Legend as in Fig. 8).