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AN ANALYSIS OF THE EFFECT OF TOPOGRAPHY ON RAINFALL IN THE TAIERI CATCHMENT AREA, OTAGO

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Abstract

In an area of 2500 square miles, consisting of the Taieri Catchment basin and adjoining areas, there are only 37 rain gauges for which there are records for more than four years. Since the topography is varied, it is difficult to estimate rainfall in ungauged parts of the catchment. This study examines the effects of four topographic factors, altitude, position, exposure and aspect on the variation in measured rainfall, explains these effects in climatological and meteorological terms, and provides the basis of a method for estimating the rainfall on ungauged areas.

INTRODUCTION

This paper records the preliminary results of an investigation into the areal and secular variations of rainfall on the Taieri Catchment. The ultimate aims of this study are, firstly, to provide methods of assessing rainfall in ungauged areas, and secondly to further the understanding of the processes involved in the action of topography on rainfall, but the work presented here is only intended to show which topographical and climatological factors are important, and to show the probable processes which are involved. It is to be noted that associated research is currently being carried out, including an estimation of the potential evapotranspiration, and a study of the point-area rainfall relationships in the area, while a further experiment, which is in the planning stage, will study these interactions in more detail in a smaller area. Research of this nature has been done elsewhere, particularly in Europe and North America, the best known, perhaps, being that reported by Spreen (1947), who correlated rainfall with topographic parameters using a graphical regression technique.

DESCRIPTION OF EXPERIMENT

The Taieri catchment covers 2204 square miles inland from Dunedin on the east of the South Island of New Zealand (Figure 7 for location), and includes parts of the climatic districts of South New Zealand and Inland South Island (Central Otago), as defined by Garnier (1958). In addition, some areas outside the catchment were included, in order to provide a sufficient number of raingauge stations, these areas being chosen on the basis of apparent climatic uniformity. The area around Dunedin was omitted, because of its distinctive climatic character, thus excluding a small part of the Taieri catchment from this experiment.

The area is one of accentuated relief, the Taieri Ridge, Rock and Pillar Range, Rough and North Rough Ridges, the Lammerlaw Ranges and the Maungatuas alternating with the Styx basin, the Maniototo, Strath-Taieri and Taieri Plains. The highest point in the area considered is Mt Ida (5548 ft A.S.L.).

Records of 11 years (1955 - 65) from 37 rainfall and climate stations were extracted from the N.Z. annual "Meteorological Observations". Although a longer time period would have been preferable, this was not possible because of the relatively recent installation of many of the gauges. Twelve of the stations were installed after 1955, but the means from these stations were used uncorrected, as there was no significant difference, when correction was tried.

Using, first, the topographic parameters suggested by Spreen, multiple regression analyses were performed, with the mean annual and mean monthly rainfall data as the dependent variables. Parameters were discarded, modified or included on the basis of their partial correlation coefficients, the final parameters being therefore somewhat different from those used by Spreen. The regression equations obtained thus indicated which were the important parameters and also provided quantitative data, which, with further refinement, could be used for the assessment of rainfall in ungauged areas.

The relationships between the topographic parameters and rainfall were then examined in the light of climatological and meteorological processes, but it should be noted that many of the conclusions reached are of a tentative nature, and require further supporting evidence.

The factors investigated were:—

Rainfall (R). Annual and monthly means, in inches, abstracted from the "Meteorological Observations".

Altitude (H). Height of the raingauge above sea level, in feet.

Distance from the Coast (D). Perpendicular distance in miles from an imaginary straight line passing close to Cook Rocks and Moeraki Lighthouse. (See Figure 1.)

Distance from a line at 90° to the Coast (S). Perpendicular distance in miles from an imaginary line drawn through Cook Rocks at 90° to the line representing the coast. (See Figure 1.)

Exposure (E). Number of degrees in a circle of five miles radius centred on the station in which there is no land higher than 1000 ft above the station.

Aspect (A). Major direction of exposure. This was coded in octants, O representing North, then clockwise round the compass to 8 representing North, and finally 9 representing North East.

Linear, logarithmic and exponential functions were tried, but the power function shown was used throughout in the final multiple regression analysis, in order to achieve uniformity, although in some cases, one of the other functions gave a better fit.

RESULTS

The multiple regression analysis gave the equations, tabulated in Table 1, these being of the form:—

$$R = C + b_h \cdot H + b_{hh} \cdot H^2 + b_d \cdot D + b_{dd} \cdot D^2 + b_s \cdot S + b_{ss} \cdot S^2$$
$$+ b_e \cdot E + b_{ee} \cdot E^2 + b_a \cdot A + b_{aa} \cdot A^2 .$$

In its present form, it is suggested that the equations are too crude to be used directly to estimate rainfall in ungauged areas, without further refinement.

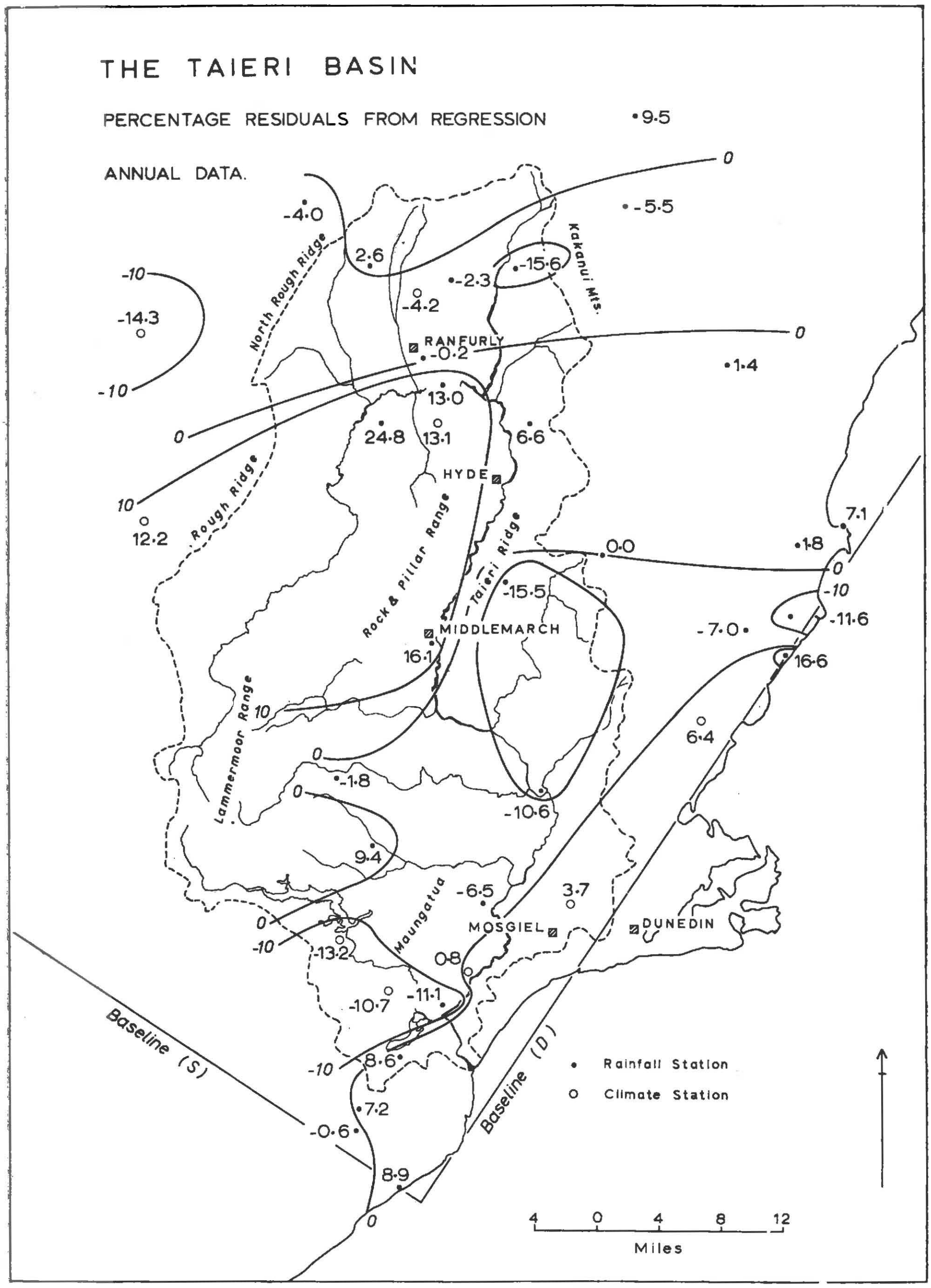


Figure 1. Percentage Residuals from Regression, Annual Data. Baselines for Parameters (D) and (S) are also shown.

Table 1. Numeric values in the regression equations.

Period	Suffix	C	b_h $\times 10^{-3}$	b_{hh} $\times 10^{-7}$	b_d $\times 10^{-2}$	b_{dd} $\times 10^{-4}$	b_s $\times 10^{-2}$	b_{ss} $\times 10^{-4}$	b_e $\times 10^{-2}$	b_{ee} $\times 10^{-5}$	b_a $\times 10^{-1}$	b_{aa} $\times 10^{-2}$	Multiple Correlation Coeff.	% Significance Level	% Explanation of Variation
Jan.	1	2.80	0.176	—1.082	4.868	—7.034	—0.720	0.122	—0.706	1.689	1.085	—2.409	0.796	0.5	63.3
Feb.	2	3.16	0.427	—0.609	0.455	—1.793	—1.530	1.278	—0.320	0.487	—0.786	1.137	0.765	1.0	58.5
March	3	2.59	0.998	—2.340	—2.574	/.803	—0.261	—0.153	0.175	—0.332	0.215	—0.724	0.666	10.0	44.4
April	4	2.77	0.584	—0.795	—1.655	0.416	—1.318	0.442	—0.583	1.100	—0.256	—0.923	0.847	0.5	71.8
May	5	2.48	0.784	—1.792	1.229	—2.251	—0.426	—0.988	—1.534	3.256	0.281	2.451	0.765	1.0	58.5
June	6	4.05	0.077	0.547	0.275	—1.402	—2.657	0.589	—0.894	1.917	—0.456	—0.557	0.909	0.5	82.5
July	7	3.20	0.816	—1.009	—6.526	3.105	0.320	—0.358	—0.462	0.893	—0.637	0.050	0.829	0.5	68.8
Aug.	8	2.07	0.399	—0.382	—2.115	1.200	—1.097	0.299	—0.045	—0.086	—1.228	0.848	0.760	1.0	57.8
Sept.	9	2.20	0.407	—0.426	—3.278	2.513	—0.827	1.112	—0.288	0.563	—0.750	0.324	0.757	1.0	57.2
Oct.	10	1.92	0.344	—0.284	0.350	—1.550	—0.231	0.309	—0.348	0.797	—0.312	—0.971	0.807	0.5	65.0
Nov.	11	3.79	0.724	—1.446	0.155	—3.456	—1.277	0.456	—0.730	1.569	—0.363	—1.495	0.856	0.5	73.1
Dec.	12	2.41	0.621	—0.129	—2.015	0.483	—0.362	—0.146	—0.099	—0.159	0.107	—0.836	0.727	2.5	52.9
Annual	13	38.23	1.702	—15.374	—8.142	—10.604	—11.168	5.0508	—7.728	15.525	—1.236	—10.744	0.864	0.5	74.2

One difficulty is that the gauges are generally placed to give a suitable exposure. Therefore, level ground, free from obstructions, is required . Thus, the effects of minor irregularities of topography are specifically excluded in obtaining the data, as is the effect of slope. It is known that the relationships between the angle of falling rain and the slope of the ground affect the catch.

Another difficulty is that the raingauges are usually placed in "hollows" in the ground, ranging in size from the Maniototo Basin to small valley bottoms, for the simple reason that observers live in such places. No results have been used in this study from gauges fully exposed on hill tops. Such results as have been obtained from such sites are not yet sufficiently long term to be useful for this analysis. Preliminary results from the Rock and Pillar Range show that a deficiency of 30% is likely, comparing gauges on the summit at 4500 ft with gauges on the eastern slope at 3000 ft (Brockie 1968).

Hovind (1965) shows, in an American experiment, that a deficiency of up to 70% is possible on the windward slope, and an excess of up to 100% on the lee slope, compared with readings taken on a summit.

The variability of the rainfall is also important. Values of the coefficients of variability for individual gauges were about 20% to 50% for the monthly data, and from 7.7% to 27.3% on an annual basis. This forbids the use of the results calculated from the 11-year means to be applied in individual years, but it has been shown in an experiment not reported here, that in this area, the correlation coefficients between stations are significant for distances of up to 70 miles between the stations. This means that when the results are calculated for *individual* years, this variability is not a serious difficulty.

Finally, since no gauge in this analysis is placed at an altitude of above 2500 ft, and only one gauge above 2000 ft, the results are applicable only to altitudes below 2000 ft, or 2500 ft, if used with caution.

Nevertheless, the analysis did provide a reasonably high explanation of the variation of the rainfall, this varying from 44% in March to 83% in June, the figure for the annual mean being 74%. Comparison of the predicted and actual annual mean values showed the maximum percentage residual to be 24.8%. Three stations showed residuals of over 16%, 14 over 10%, 24 over 6%, and 13 stations within 6%. This is shown graphically in Figure 1. These results must be considered satisfactory in view of the known inaccuracy of raingauges, which may be up to or in excess of 10%.

The real test of the equations would be to apply them to stations not included in the analysis. In order to avoid bias, a number of such stations should be used. Table 2 shows relevant data calculated from a number of stations not included in the analysis.

Table 2. Actual and calculated values of annual rainfall, for stations not included in the regressions.

Site Location	Authority	Actual Annual Value, ins.	Predicted Value, ins.	Residual %
Maungatua	Mark (1965)	20.6	28.9	+40.1
Maungatua	Mark (1965)	35.3	40.33	+14.2
Moa Creek	Met. Office	14.5	16.90	+16.5
Trotters Creek	Met. Office	25.5	30.53	+19.5
Puketoi	Mrs B. Smith (1967)	17.99	18.96	+5.3
Dansey's Pass	Otago Catchment Board (3067 ft A.S.L.)	22.1	13.3	—43.1

As may be expected, the percentage residuals are generally greater than those from the analysis, but, apart from one station on the Maungatua, the errors are not excessive.

In examining the individual effects of the topographic factors, it was borne in mind that the production of rainfall depends principally on the general condition of the atmosphere, i.e. its temperature, humidity, and vapour pressure distributions and the vertical motion of the atmosphere. The explanation for the relationships between rainfall and the topographic parameters was thus sought in the effect which these parameters would have on the general condition of the atmosphere, and on its vertical motion.

Effect of Altitude (H)

Giving mean values to the other variables, the relationships between rainfall and altitude are shown in Figure 2. The upper graph shows the effect of altitude

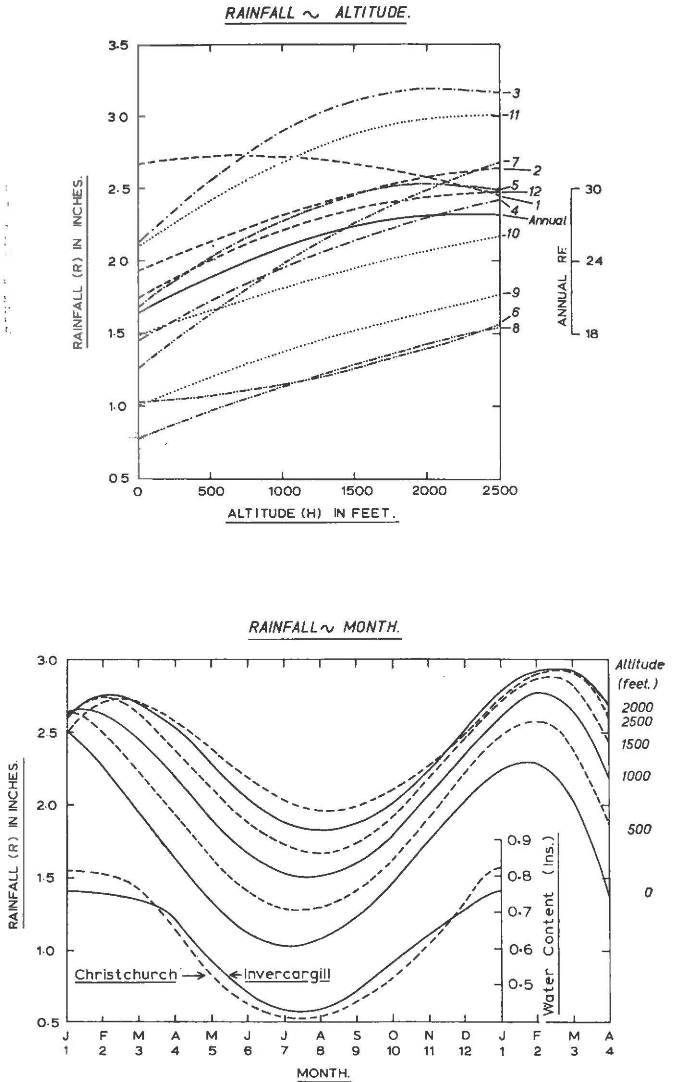


Figure 2. The Effects of Altitude (H) on Rainfall.

on the predicted values of rainfall for each month and for the annual mean. It will be seen that, except for January and June, an increase in height causes an increase in rainfall, but that the rainfall/altitude gradient decreases with increasing altitude. In some cases a maximum rainfall occurs within the altitudinal limit. The annual gradient, for example, is 7.02 inches/1000 ft at sea level, but falls off to zero at 2280 ft, above which height, increasing altitude incurs decreasing rainfall. Although the Octapent raingauge at Dansey's Pass (3067 ft A.S.L.) showed only 11.84 inches for 202 days in 1964, 22.15 inches for 344 days in 1963, and only 0.87 inches in December 1961, equivalent to about 22 inches/year, this result is surprising, and was investigated more closely, using three methods.

(i) The data for the gauge at 2448 ft (Manorburn Dam), which, recording particularly low rainfall figures, were thought to have a disproportionate effect on the results, were omitted from a recalculation of the equations. This resulted in the rate of change of the annual gradient, with altitude, being much reduced, with a theoretical maximum rainfall occurring at 8070 ft. In some regressions on the monthly data, little difference was noted, and in all cases, the effect of omitting this station was small below 2000 ft.

(ii) The area was divided into three zones, coastal, intermediate and interior, and the data from the zones was analysed separately, the results being shown in Figure 3. The "interior" regressions showed a marked peak at about 2000 ft, while the "intermediate" regression, with its highest station at 1800 ft showed no such trend. It is thus possible that the peak is, at least in part, a phenomenon local to the interior zone, or that the Manorburn Dam gauge unduly affected the results.

(iii) Using a method demonstrated by George (1967), cumulative curves of the level of convective cloud bases were plotted (Figure 4) for Christchurch and Invercargill. These curves show, not the actual levels of the cloud bases, but the percentage occurrences of cloud if the atmosphere had been lifted through the given heights, either by convection or orography.

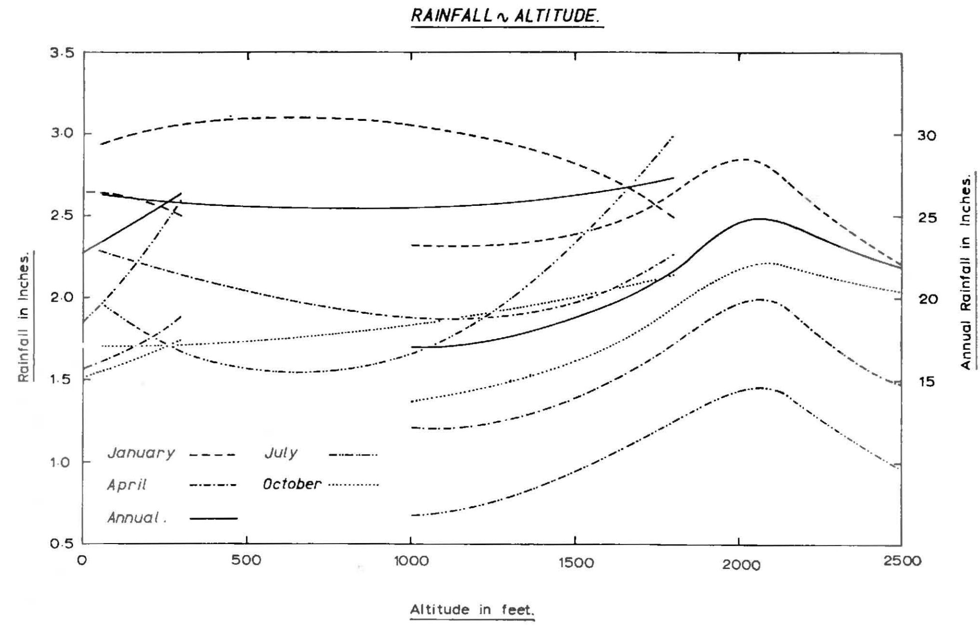


Figure 3. Zonal Rainfall — Altitudinal (H) Relationships.

Assuming a relationship between the occurrence of cloud and the occurrence of rainfall, it may be seen that vertical motions greater than 2000 - 3000 ft should have little effect on the *occurrence* of rain, although the variations in saturated vapour pressure should affect the *intensity* of rainfall. In January, once condensation occurs, a rise of 1000 ft nearer sea level should produce more rain than a similar rise at higher altitudes, since the saturated vapour pressure curve levels out, and hence less vapour will be precipitated. This effect, however is not significant during winter, when the saturated vapour pressure curve is almost linear.

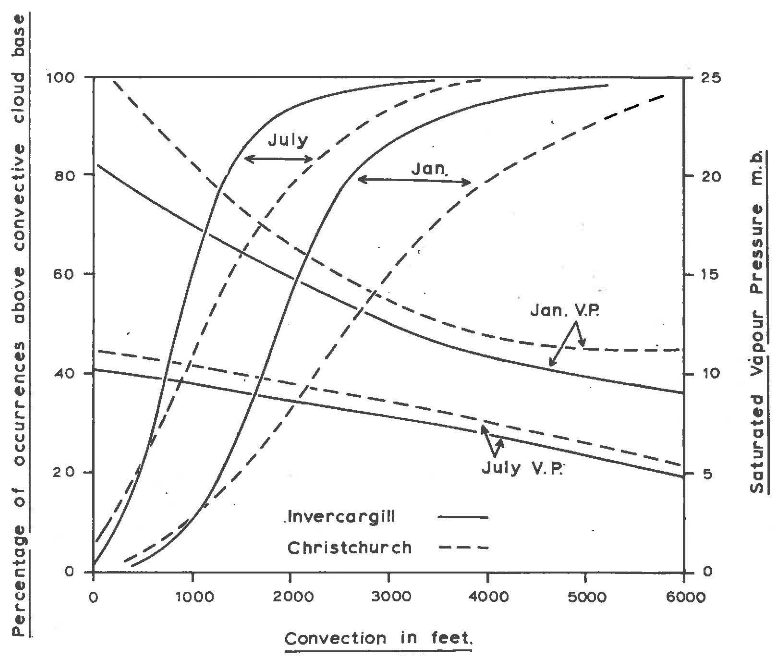


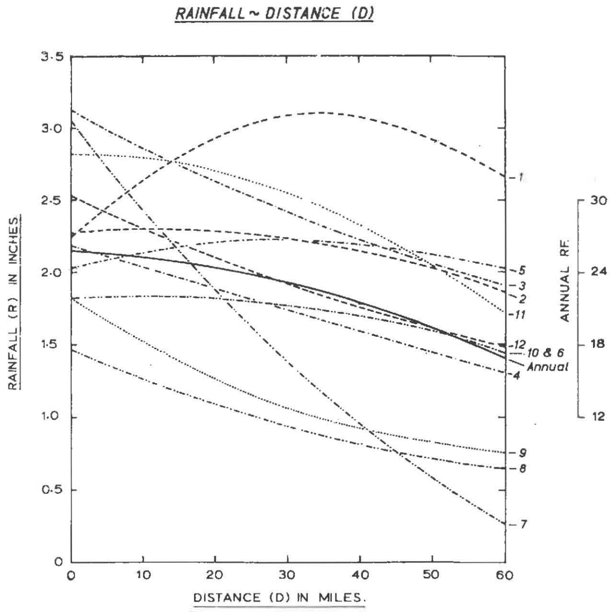
Figure 4. The variation of the percentage occurrences of convective cloud cover, and saturated vapour pressure, with altitude.

On these grounds, it is evident that the effect of altitude should be to produce a maximum rainfall at some elevation, the indications in this area being for a value of between 3000 and 6000 ft depending on the season.

The lower graph in Figure 2, derived from the upper by smoothing predicted rainfalls throughout the year for selected heights, shows clearly the summer rainfall maximum, which is related, not to the relative humidity at ground level, but to the water vapour content of the atmosphere, shown in Figure 2, which was derived from data from the two nearest radiosonde stations, Christchurch and Invercargill (N.Z. Met. Service, 1961) using a method shown by Ananthakrishnan, Selvan and Chellappa (1965).

Of more interest, however, is the seasonal variation of the importance of altitude, as shown by the relative separations of the curves. The condition of the atmosphere, and its vertical movement both influence this seasonal variation of rainfall.

In winter, the main agent for vertical air movement is orography, hence rainfall is more closely associated with altitude, but in summer, the main agent is convection. It may be assumed that initial lifting of the air takes place over valleys, but with convection currents rising to 30,000 ft, and with varying wind velocities, the resulting rainfall is randomly scattered. In addition, where orography does play a part, as shown above, there is a linear relationship between precipitated vapour and orographic lifting in winter, but a non-linear relationship in summer.



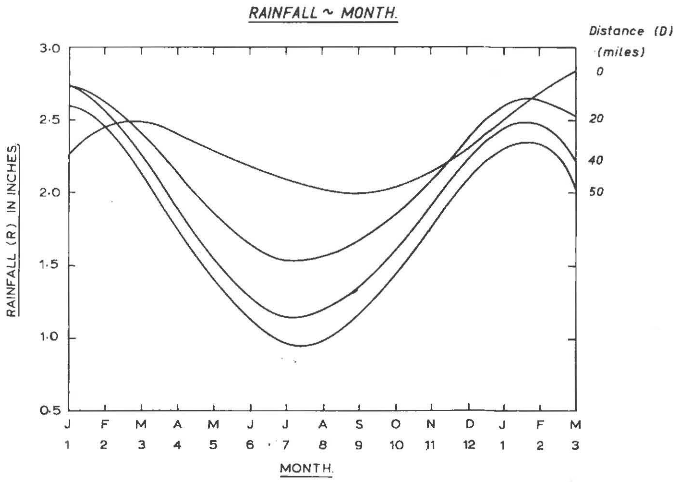
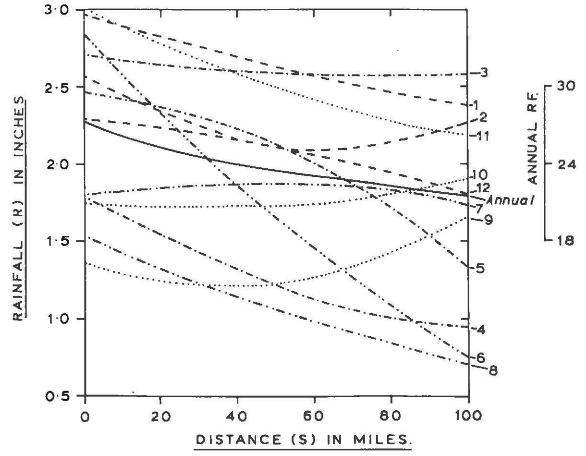


Figure 5. The effect of distance (D) on rainfall.

Effect of Position (D.S.)

It is well known that, in the south of the South Island, rainfall decreases away from the coast and from the main Divide, achieving a minimum somewhere near Alexandra, and this is substantiated by the results shown in Figures 5 and 6.

Rainfall generally decreases with increasing distance from both base lines. It is evident that this effect is most marked in early winter, and least marked in early summer.



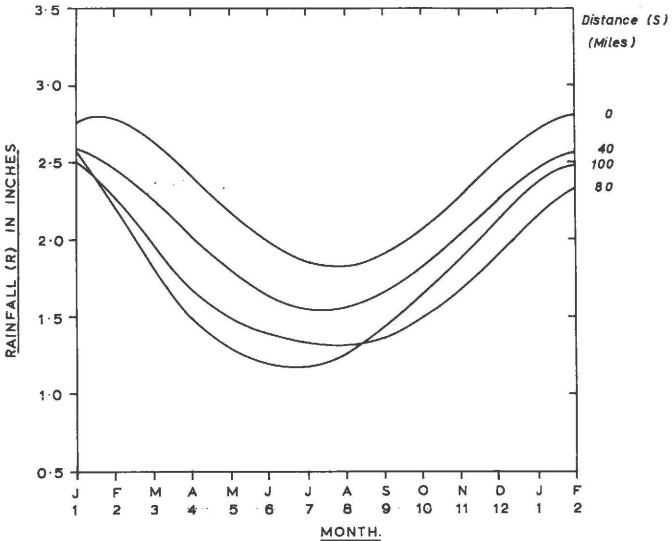


Figure 6. The effect of distance (S) on rainfall.

Rainfall, in this context can be closely connected to vapour pressure. Figure 7 shows annual values of vapour pressure and calculated annual rainfall. Considering that the vapour pressure curves were drawn by eye, while the rainfall curves are restricted to second order shapes, the qualitative correspondence is good. Figure 7 also indicates the relationship between rainfall and vapour pressure in and around the Taieri Basin. This relationship does not, however, apply to other areas.

Seasonal variations in the effect of position can also be explained by variations in vapour pressure (Figure 8). During winter, June being taken as an example, position has an important effect on rainfall, and this can be related to vapour pressure. Since, from the work of Browne, (pages 90, 93, 94, 1950), it may be assumed that it is the southerly and easterly winds which are the predominant rain producers, it is obvious that vapour pressure, and hence available moisture will decrease as the air passes over the land; the condition of the atmosphere, rather than the vertical motion experienced, is the dominating influence. The geographic distribution of rainfall, indicated in the lower graphs of Figures 5 and 6, corresponds with the vapour pressure distribution plotted for June in Figure 8, which also shows the positive relationship between vapour pressure and rainfall.

However, due to the predominant effect of convectional vertical atmospheric motion in late spring and summer, the condition of the atmosphere is less important. Vertical atmospheric motion is likely to be stronger inland, during daytime, counteracting the effect of the lower vapour pressure. Hence the relationship between vapour pressure and rainfall, as shown, is much less marked.

Further, comparing the North West and South East of the catchment, a difference of two millibars vapour pressure occurs in winter, and a difference of only one millibar during summer. Thus when the condition of the atmosphere is important, it is to be expected that position, measured in terms of D and S, should be more important in winter, than in summer.

The results are comparable to those of Platzman (1948) who established a linear relationship between rainfall and dew point at one location in Oregon.

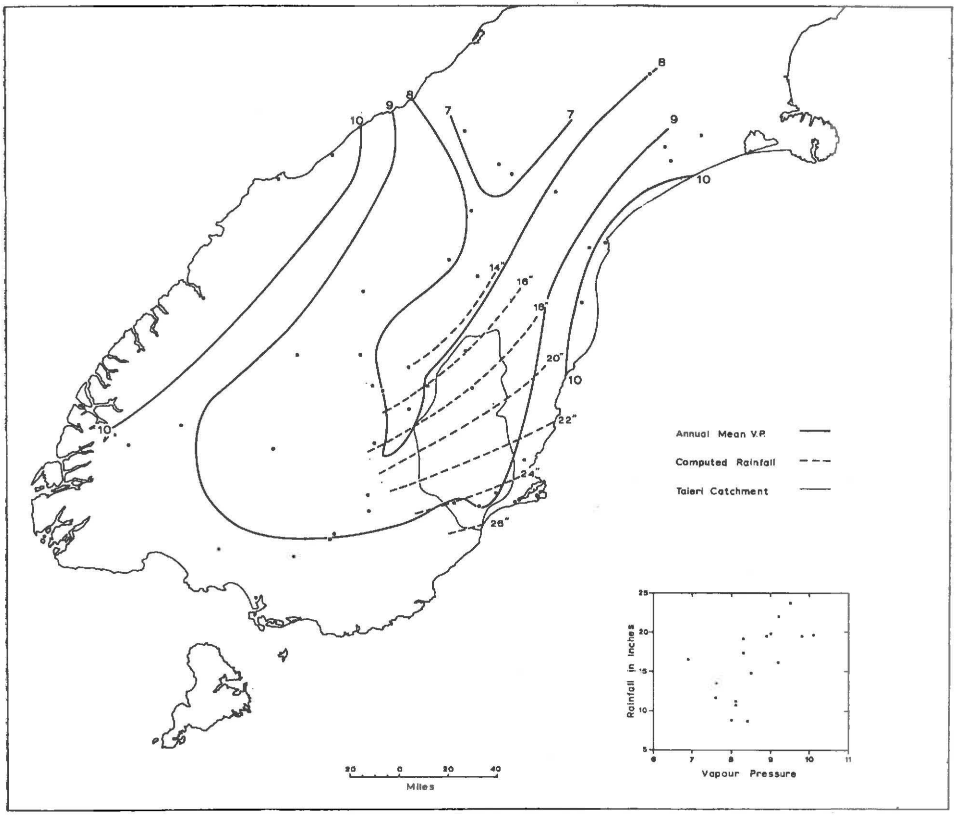


Figure 7. The relationship between position, annual mean vapour pressure, and rainfall.

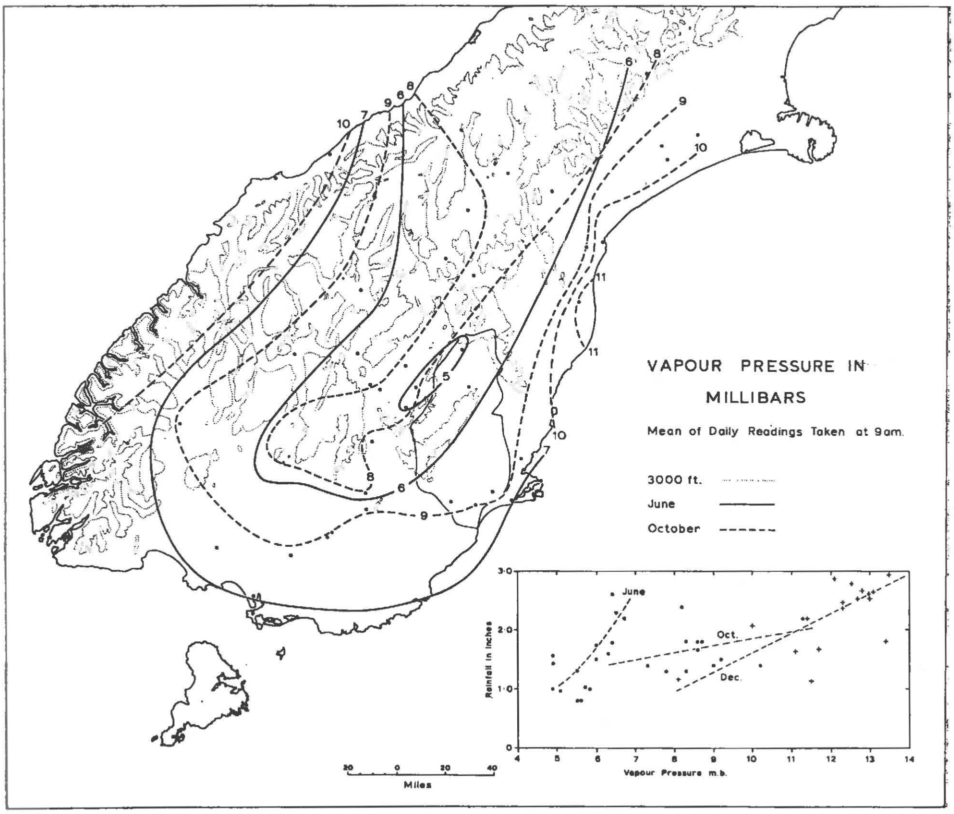


Figure 8. Seasonal variations in vapour pressure and rainfall.

Effect of Exposure

Few research workers have investigated the effect of exposure on rainfall and no satisfactory explanation has yet been offered to account for this effect. Spreen's results agree, to some extent, with those presented here, but no explanation was given.

The results (Figure 9) show in almost every case that as exposure increases, rainfall decreases, until at about 250°, rainfall begins to increase.

One possible reason, which has not yet been confirmed or refuted is that when exposure is low, the gauge being thus situated in a hollow, the horizontal wind velocity across the mouth of the gauge is much reduced. The angle of fall of the rain is thus much nearer vertical, the gauge mouth presents a greater area perpendicular to the direction of fall, and hence the catch is high. This does not, however, explain the increasing rainfall at large exposures.

The seasonal variations of the importance of exposure shows that the effect is greatest in late autumn and early winter, which would be expected from the above considerations concerning the condition and vertical motion of the atmosphere.

Effect of Aspect

It could have been expected that the relationship between aspect and rainfall would have obeyed some form of circular function. Several types of circular function were tried, but none were as significant as the method here presented, which has, however, an element of subjectivity.

The importance of aspect can be explained using the known orographic effect of topography. A gauge which is on the windward side of a hill crest receives more rain than one on the lee side, this effect being generally increased when, as is common, the gauge is surrounded on three sides by higher ground. For example, a gauge on the easterly slopes will receive high rainfall from easterly winds. But monthly and annual data includes rainfall occurring with all wind directions. The moisture content of air approaching from any direction thus becomes important, and it has been shown previously that there is a decrease in vapour pressure inland from the coast. Thus it may be postulated, from commonsense considerations, that there will be some inverse relationships between the distance over dry land over which the air has flowed, and its moisture content, and hence its capability to

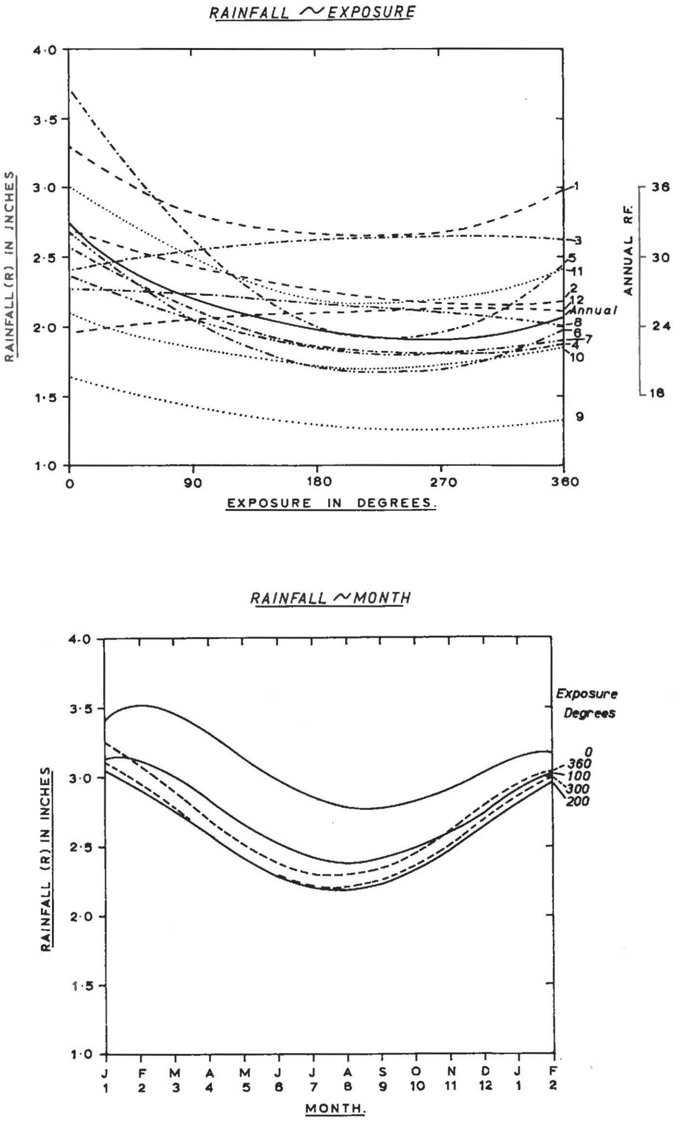


Figure 9. The effect of exposure (E) on rainfall.

produce rain. In further explanation, a hypothetical example is given. Assume that twice as much rain falls on the windward slope as on the leeward. At a position near the east coast, easterly winds produce rain, say 20 inches/year on a gauge open to the east, and therefore 10 inches/year on a gauge open to the west. Westerly winds may produce half as much rain, the figures then being 10 inches/year on the gauge open to the west, and five inches/year on the gauge open to the east. The totals are therefore 25 inches/year in the gauge open to the east, and 20 inches/year in the gauge open to the west.

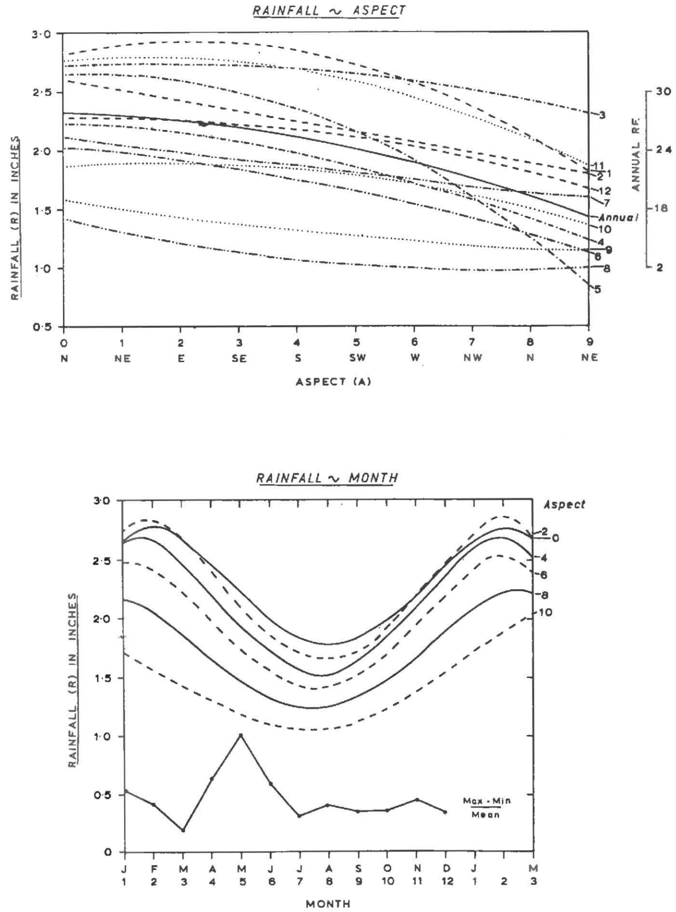


Figure 10. The effect of aspect (A) on rainfall.

Figure 10 indicates on an annual basis and for most months, a decrease in rain from the North East round through South to the North.

There is, however, a complication. Owing to the position of the Taieri Basin, wind approaching a gauge from the North-east may have travelled overland from the north of the South Island, or may have just been diverted in from the nearby coast, the "distance of overland flow" being determined by the relative topography. The method of arriving at the equations was thus to code the aspect from 1 representing North-east, thence clockwise in octants to 8 representing North. Regressions on aspect and rainfall were then determined, and a comparison made between actual and predicted rainfall values. Where there was a gross error (> 20%) for aspects of N. or N.E., the code figure of 8, or 1 was replaced by the code figure of 0 or 9, respectively, if an improvement resulted. This was done only on the basis of residual, but examination of Figure 11 shows that the correct code number is tied to the position of the gauge.

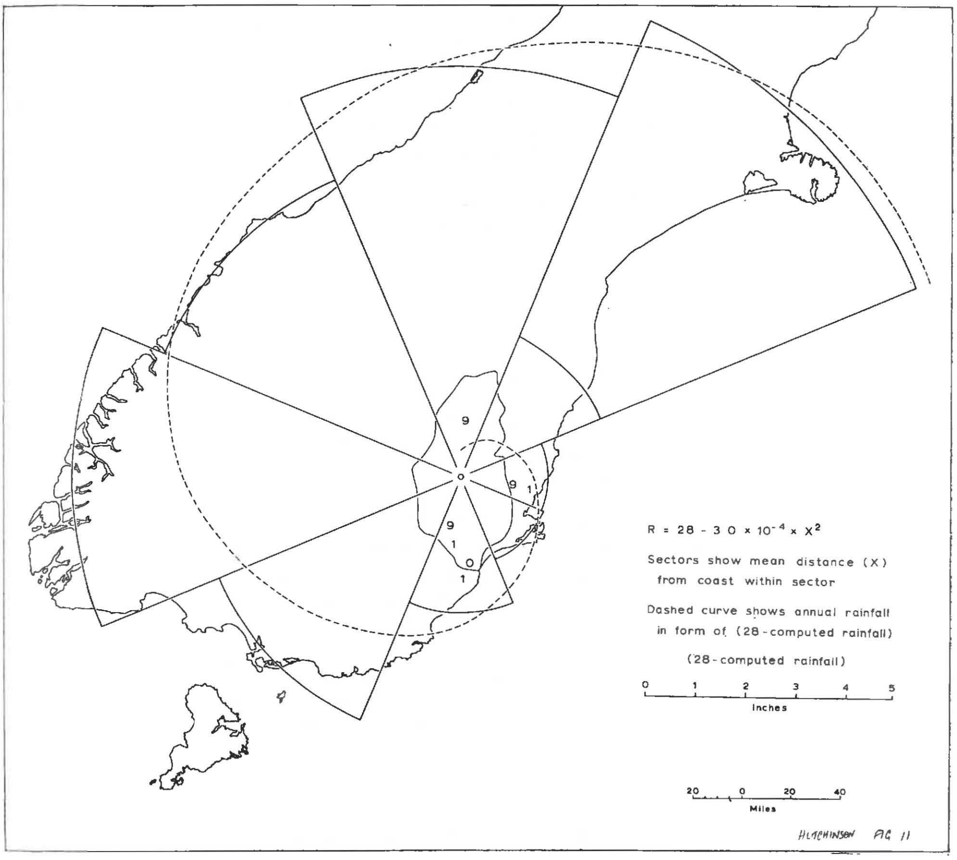


Figure 11. The relationship between annual mean rainfall, aspect and "length of overland flow".

When using the equations to predict, and if the relative aspect is N., or N.E., then a subjective judgement must be made. The difference in the final predicted rainfall could be eight inches per year, but examination of the location of the position and likely streamlines should enable a choice to be made.

The results (Figure 10) show the variations in rainfall for each month, and for selected aspects. It may be clearly seen that the rainfall decreases, for the year, and for each month, as aspect rotates from North, clockwise through South to North East . The actual difference between an easterly and a westerly exposure, used in the example, is 3.9 inches per year.

The monthly variations of the effect of aspect are not great. The difference between the maximum and minimum rainfall values is greatest in February (1.2 inches/month) and smallest in August, September and October (0.7 inches/month). This variation, however, is more apparent than real, since the ratios of difference between maximum and minimum predicted values to mean values, show no seasonal variation. The relevant ratios are:

February	0.54
August	0.64
September	0.53
October	0.43

There is, however, a seasonal difference, in that while the rainfall/aspect gradient is uniform in winter (as shown by the even spacing of the rainfall values for selected aspects), this is not so in summer. A change of a few degrees of an easterly aspect makes little difference to rainfall, while a change of a few degrees of westerly aspect makes a large difference to rainfall. It is possible that this is associated with the mean monthly positions of anticyclones, which vary from 32.2°S in September to 38.0°S in February, according to Kidson (1932) due to the greater wind variability, in strength and direction, in February, but further investigation is needed before any definite conclusion can be reached.

The connection between rainfall, aspect, and "length of overland flow", is shown in Figure 11. The sectors show the mean distance of the coast in each octant, from the centre of the catchment area. Two values are shown for the North East Octant, one showing mean values for the sectors between N. 22.5°E. and N. 45°E., the other between N. 45°E. and N. 67.5°E.

The approximate relation:

$$R = 28 - 3.0 \times 10^{-4} \times X^2$$

where R = Annual mean rainfall in inches

X = Distance of catchment from coast in the direction of exposure,

was established by plotting a suitable graph. Choosing a suitable scale, values of (28 — R) were plotted on Figure 11 thus showing a correspondence between predicted rainfall and length of overland flow. In fact a closer correspondence is obtained if X is raised to the power 3/2, but the squared term is used here for simplicity.

The least correspondence is seen to be for the lesser values for the N. and N.E. directions. Figures shown on Figure 11, however, indicate that the high rainfall choices (0, 1) lie near the coast, so that the actual "distances of overland flow" are less than indicated by the sectors.

DISCUSSION AND CONCLUSIONS

The results show that each of the topographic parameters considered can have a considerable effect on the variation in rainfall. For comparative purposes, Table 3 shows the range of effect of the factors, within their numeric limit. Not shown in the table, however, is that for each parameter there are months for which their effect is minimal.

Table 3. Range of computed rainfall due to effect of each factor.

Factor	Range of Factor	Range of Rainfall, inches Annual	Greatest Month
Altitude (H)	0 - 2,500 ft	8.0	1.4
Distance from Coast (D)	0 - 60 miles	7.6	2.0
Distance parallel to Coast (S)	0 - 100 miles	6.1	2.1
Exposure (E)	0 - 360°	7.0	1.8
Aspect	0 - 450°	9.6	2.2

It is interesting to note that no one parameter has an over-riding importance on an annual basis, although there are months for which rainfall is most dependent on one parmeter, for example, June rainfall is most dependent on distance (S) from a line perpendicular to the coast.

The results, in general, agree with those from previous research.

A direct relationship between rainfall and altitude has been previously shown by several workers, but, contrary to the present results, both Spreen, and Peck and Brown (1962), find an *increasing* gradient as altitude increases, no maximum rainfall being obtained even for heights up to 10,000 ft. A decrease in the rainfall gradient has been observed on the West Coast of the United States, but it is thought that this was at least partially due to the reduction of catch by strong wind action. It is known that in some tropical areas maximum rainfall occurs at about 6 - 8000 ft, but the general atmospheric condition is rather different, and cannot be taken as a comparison. It is thus necessary that further investigation is required on the rainfall-altitude relationship, and it is intended that a mathematical analysis be carried out. This type of analysis has been done previously by several workers, especially Sarker (1966), for individual storms, but little has been published for longer time intervals.

The effect of distance (D and S) compares well with results of Peck and Brown, who found such relationships in Utah. However, because of the nature of these factors, their effect must be essentially unique to any geographic district. The results of Browne also confirm the conclusions reached in this experiment.

Spreen, using a 20-mile radius for his exposure measurement showed for winter months that maximum rainfall occurred with an exposure of about 90°. Qualitative agreement with the present results occur at values of over 90°, but not under 90°. Rodda (1962) using only a linear regression found that an increase in exposure resulted in a decrease in rainfall. This simple relationship would have appeared in this experiment if a linear regression had been used. The main difficulty in assessing the effect of exposure is the lack of any obvious causal relationship, and hence difficulty in choosing the quantities used in the original definition of exposure. Spreen uses a 20-mile radius, while Rodda uses only one mile radius. Various radii were tried in this experiment, the five-mile giving the highest correlation with rainfall, but it is not supposed that the relationship is as simple as this single figure suggests.

By its nature, aspect is again a factor whose effect is unique to a particular geographic location. The general form of the relationship, however, in that a non-circular function provides a better fit than a circular, is also evident in Spreen's results, where the break occurs at a South-easterly aspect.

As a predictive tool, the method used is not, at present, adequate for all purposes. Although it has been shown that it is probable that predictions would have an error of less than 20%, which would be satisfactory for some needs, in actual practice, what is often required is effective precipitation, i.e. rainfall less evaporation, or rainfall less evapotranspiration. Thus, what is required is the difference between similar quantities, necessitating a much higher accuracy than that needed where no difference is involved. However, further refinement is possible and there seems no reason why a sufficient accuracy could not be achieved.

It is realised that, in this study, not all relevant factors have been included, the most important of which is probably wind. The records which are available, however, were not considered to be totally suitable for use in this analysis. Where climate stations within the experimental area record wind velocity, it is thought that local factors influence the wind too much for the results to have general application. Where upper air soundings are available, at Christchurch and Invercargill, the records were considered applicable where the general condition of the airmass is important, but not to local phenomena, such as wind velocity.

Finally it is necessary to emphasise that many of the conclusions reached are of a tentative nature, particularly those where climatological and meteorological processes are involved, but work, as outlined above, is proceeding to confirm or refute these conclusions.

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