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Rainfall enhancement over the Waitakere Ranges of West Auckland, North Island, New Zealand

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Abstract A preliminary investigation of rainfall distribution over a raingauge array situated in the Waitakere Ranges of West Auckland, North Island, New Zealand, during the passage of four cold fronts, has revealed a systematic orographic influence on two occasions. The rainfall on these occasions increased substantially with distance from the coast, whether the gauge array was, by virtue of the low-level wind direction, on the lee side or windward side of the hills. The present studies suggest strongly that rainfall rates at sites with different enhancements are linearly related. Catch ratios of up to 3:1 were measured for offshore winds. These studies are distinguished by the dense network of gauges used.

Keywords orographic rain; rainfall enhancement; raingauge array;

INTRODUCTION

The enhancement of rainfall by local effects associated with low hills is a well-known phenomenon for which an explanation was first provided by Bergeron (1965). Bergeron proposed that low hills under certain conditions will generate a local cloud system in the airflow through which rain from synoptic-scale systems can fall. The low clouds themselves produce little or no rain, but conditions within them are conducive to the growth of raindrops falling from the higher level clouds. The low-level clouds are replenished by the moist, low-level airflow. Thus, the intensity of rainfall beneath regions where the local (or feeder) cloud exists is greater than that from the widespread upper (or seeder) cloud. The process has been modelled by a number of workers, notably Storebo (1976), Bader & Roach (1977), Gocho (1978), Carruthers & Choularton (1983), and Robichaud & Austin (1988), and observations of the phenomenon have been made by Browning et al. (1975) and Hill et al. (1981). Whilst there is a measure of qualitative agreement between theory and observation, there remain discrepancies regarding the degree of dependence of rainfall enhancement upon low-level windspeed and upon seeder rainfall rates. For example, although theory predicts that rainfall enhancement will increase as the low-level windspeed increases, observations to date suggest that the rate of increase of enhancement is much greater than theory will allow. Also, whilst Bader & Roach (1977) predicted a strong dependence of enhancement on seeding rate, the observations of Hill et al. (1981) are consistent with a weak dependence.

The Waitakere Ranges of West Auckland were chosen for a preliminary study for a number of reasons: proximity to the University of Auckland; frequent appearance of low-level cloud over the ranges; lack of any previous assessment of rainfall enhancement in the region; and much of the region is under controlled access through the Auckland Regional Authority Parks and Reserves Department and the Auckland Regional Water Board. Furthermore, there is a need to fully assess the New Zealand environment, and the Waitakere Ranges region, which contains several reservoirs, is an example which should receive particular attention. In performing the work described below, our primary aim was to further understand the rainfall enhancement process. However, the data obtained can also be of immediate usefulness to organisations involved in, for example, water resource management or storm-water drainage.

DESCRIPTION OF THE SITE AND THE INSTRUMENTATION

The Waitakere Ranges are a series of hills on the coast west of Auckland. The terrain rises from sea level to a height of 400 m at a grade of approximately 1 in 10 and is comprised mainly of dense regenerated native bush. The ranges are, in general, perpendicular to the prevailing southwest wind. The ranges represent an ideal site remote from the public, but of suitable scale for orographic rainfall studies. The raingauge spacing was approximately 1 km, with exact placement of gauges dependent upon the availability of clearings which satisfied the "2 in 1" criterion described by Sevruk (1982). Figure 1 shows a plan and profile of the Waitakere Ranges in the region of the raingauge array and also the gauge placement. Table 1 gives the distance from the coast and the altitude (a.m.s.l.) of each gauge site. The array consisted of seven gauges in a line running approximately southwest–northeast, with an equal number of side gauges. The large-scale precipitation areas associated with the frequent cold fronts generally move in a direction parallel to the main gauge line. The side gauges provide a measure of the lateral variation of the rainfall. The size of an observed precipitation area needs to be such that it

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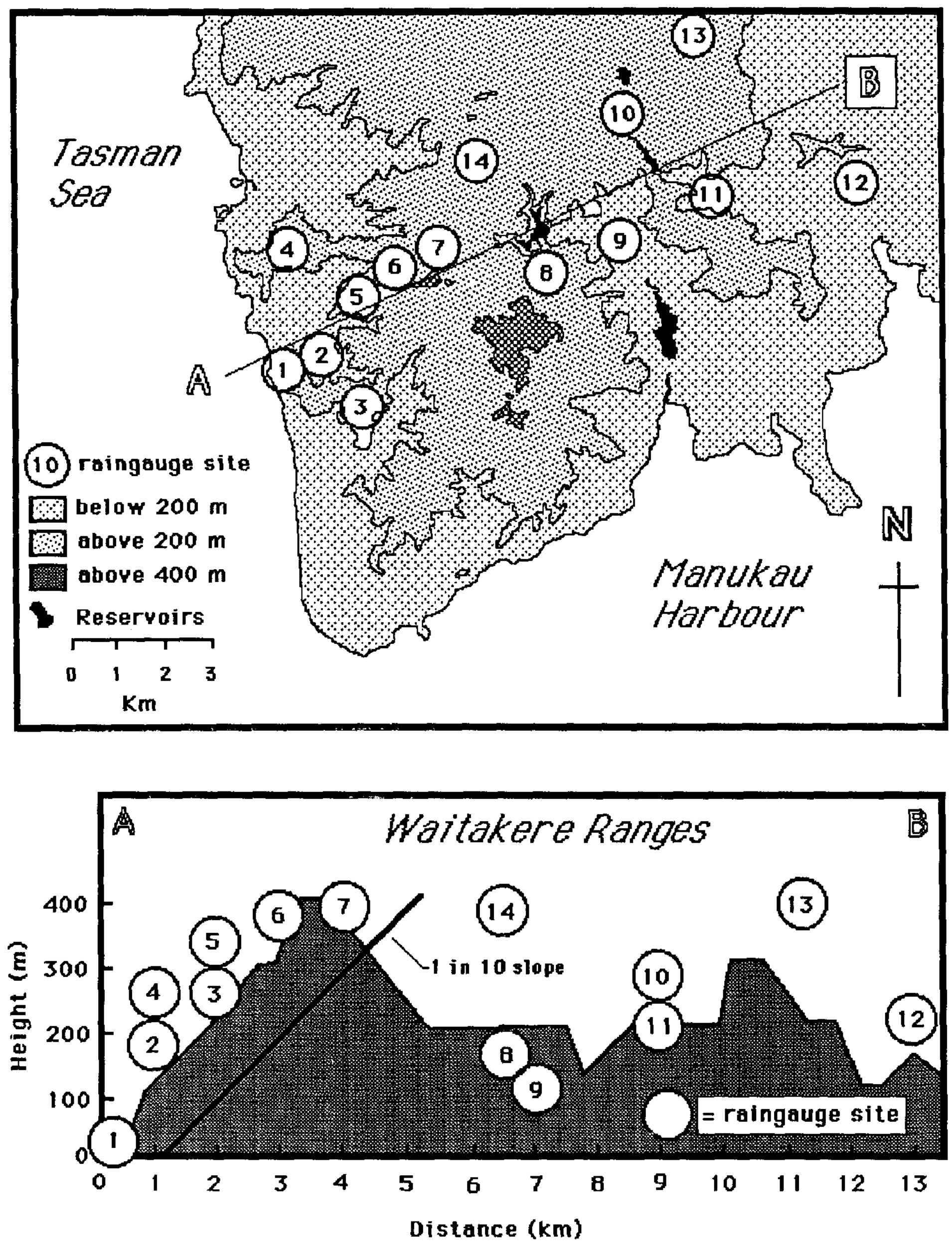

Fig. 1 Plan and profile of the Waitakere Ranges in the vicinity of the raingauge array. Not all gauges are on the profile line shown, but the relative locations from the coast and height (a.m.s.l.) of gauge sites is given.

will pass through all gauge sites equivalently, requiring a scale length perpendicular to the wind (or gauge line) of the order of 10 km. Smaller systems can be expected to give an incorrect measure of enhancement, as discussed by Browning et al. (1974).

Table 1 The distance from the West Coast and the height (a.m.s.l.) of each Waitakere gauge site.

Gauge no.	Altitude (m)	Distance inland (km)
2	180	1.0
3	300	2.0
4	260	1.0
5	280	2.0
6	380	3.0
8	160	6.5
9	100	7.0
10	280	9.0
13	380	11.0
14	380	6.5

The raingauges used were similar to that described by Hosking et al. (1986), except that gauge units were powered independently by batteries and carried RAM for data storage. In the preliminary investigation described here, the RAM size was limited to 2048 bytes, requiring for logistical reasons that gauge sampling intervals be set to either 512 or 1024 s. Gauges were calibrated in the laboratory and recalibrated after each significant rainfall event. Their calibration was found to fluctuate by not more than ±5% over the duration of the project, each gauge generating about 150 equal-sized drops per millimetre of rainfall. Using the treatments described by Gertzmann & Atlas (1977) for a sampling time of 512 s, the total fractional gauge error in determining rainfall intensity due to sampling, quantisation, and drop-size variation errors is <3% for intensities in excess of about 2 mm/h. For a sampling time of 1024 s, the total fractional error is <2% under the same conditions. Unlike the gauge network described by Hosking & Stow (1985), the sampling in the present experiments is asynchronous.

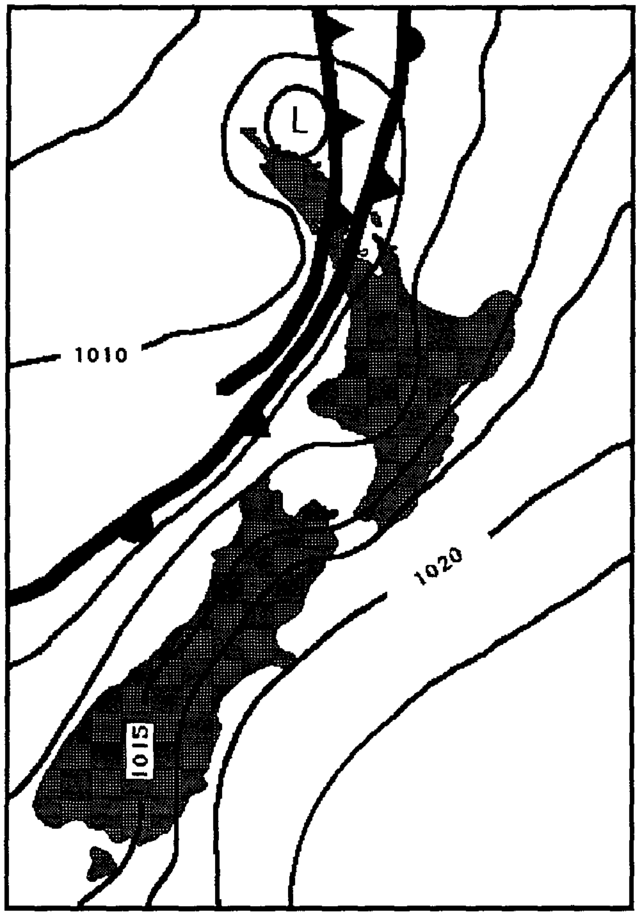

Fig. 2 Case study 1. The surface synoptic chart for 1200 NZST on 11 December 1984.

Table 2 Case study 1. Total gauge catches and the number of 512 s sample periods during which the mean rainfall intensity exceeded a given threshold. (A) Lee-side data prior to the passage of the cold front. (B) Post-frontal data when the gauge network was to the windward side.

A

		Pre-frontal threshold level (mm/h)				
Gauge no.	Total catch (mm)	0.1	1	2.5	5	10
10	130	89	65	35	28	13
14	137	99	58	40	25	17
8	119	89	57	38	24	13
6	88	97	40	28	18	8
5	86	101	52	30	16	7
4	72	63	34	26	13	5

B

	Post-frontal thresholds level (mm/h)				
Gauge no.	0.1	1	2.5	5	10
10	36	34	24	18	8
14	36	26	23	20	14
8	31	29	24	20	9
6	30	25	23	17	3
5	30	27	25	18	6
4	33	27	25	20	11

RESULTS AND DISCUSSION

Between December 1984 and January 1985, four case studies were made, the first two using sample periods of 512 s, the second two using 1024 s. The relatively high density of the gauge network used here is unique. Surface synoptic charts, wind-field plots, and 800 mb analyses were obtained from the New Zealand Meteorological Service. No radar data or local balloon-sounding data were available.

The catches of each gauge were compared by two methods. In one method, threshold rainfall rates were selected (0.1, 1, 2.5, 5, and 10 mm/h) and the number of sample periods exceeding these thresholds were counted for each gauge. Generally, the gauges with the higher rainfall rates and catches will have more counts above a given threshold. In the second method, records from the gauge with the greatest catch were compared with records from other gauges by pairing intensities for any given interval of time and performing a least-squares linear regression. In widespread rain (as defined above), the gradient of the regression line will be a measure of the degree of orographic enhancement between the pairs of gauge sites. Furthermore, if the process causing the enhancement is consistent in character, correlation coefficients should be high. The enhancement referred to below is the ratio of two rainfall rates rather than "incremental enhancement" which is the difference between two rainfall catches.

Case study 1: 11 December 1984

A period of frequently heavy rainfall lasting about 12 h was generated by the passage of a complex cold front associated with an embedded depression. The surface synoptic chart is shown in Fig. 2 and depicts the cold front lying northeast–southwest, preceded by a moist, warm airflow from the north. The surface wind backed from an easterly of 5–12 m/s to a westerly of 5–9 m/s. The large change in the direction of the surface wind resulted in an unusual situation, causing the gauge array to first be on the leeward side of the range and then on the windward side. Figure 3 shows the rainfall records obtained for the event; six gauges were in operation at that time, namely, gauges 4, 5, 6, 8, 10, and 14. The rainfall event was clearly divided into two parts (near sample 1020), and this coincided with the change in surface wind direction, at which time precipitation ceased for a short time. Browning et al. (1975) observed, in their study of orographic influence on rain in South Wales, that each section of the passage of a front had different orographic enhancements. Comparison of this observation with the present results must be made with caution because the Waitakere Ranges are relatively short.

Table 3 Regression analysis of raingauge records, using gauge 14 as the reference gauge, for case study 1. The gradient corresponds to the gauge catch ratio over all rainfall intensities. The correlation coefficient is a measure of the independence of gauge catch ratio from rainfall intensity.

	Pre-frontal		Post-frontal	
Gauge no.	Correlation	Gradient	Correlation	Gradient
10	0.73	1.16	0.80	0.98
8	0.84	1.19	0.95	0.87
6	0.83	0.43	0.93	0.66
5	0.78	0.38	0.92	0.61
4	0.62	0.35	.095	0.84

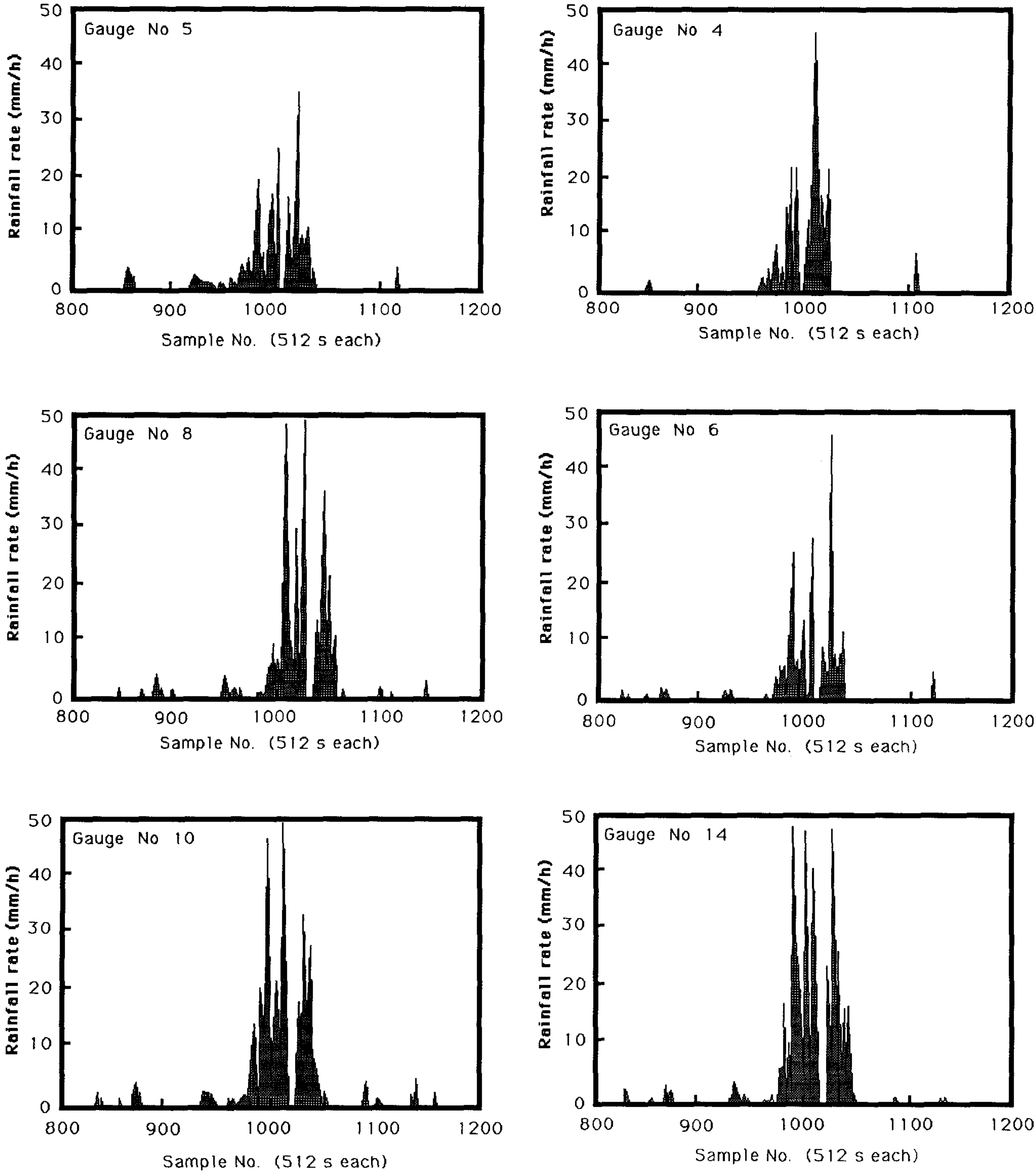

Fig. 3 Case study 1. The rainfall intensity records for the gauges operating during the event. The sample period is 512 s.

Table 2 shows the total rainfall catch for each gauge and the rainfall intensity threshold statistics for the two portions of the rainfall event. The greatest catch overall was by gauge 14, with other gauges showing a monotonic decrease in catch towards the coast. Gauge 14 also generally shows the greatest number of samples exceeding a particular intensity. The results using the least-squares regression against gauge 14 are shown in Table 3. From these data, it can be concluded that there is a less-pronounced pattern of rainfall enhancement when the gauge array lies on the windward side, which may be related to the asymmetry of the hill profile. Also, in the earlier rainfall period, the least-squares method shows that both gauge 8 and gauge 10 recorded a greater enhancement than gauge 14. Also, the method shows that gauges 4 and 5 collected only 35–38% of the rainfall compared to gauge 14 in the pre-frontal period, but 60–68% in the post-frontal period.

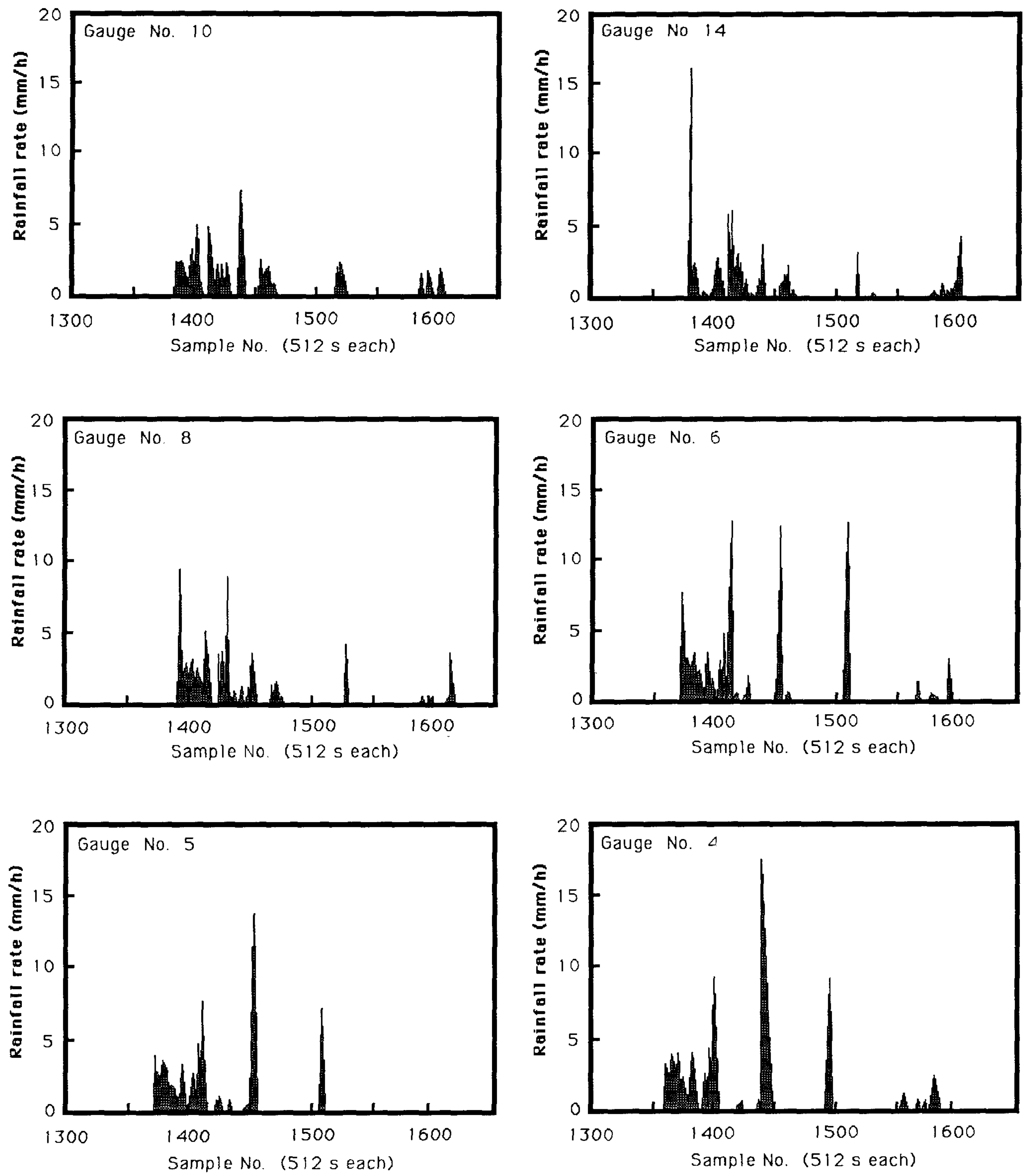

Fig. 4 Case study 2. The rainfall intensity records for the gauges operating during the event. The sample period is 512 s.

The high correlation coefficients suggest strongly that the relative enhancements between one gauge site and another are independent of rainfall rate. Gauge 4 does not fit the sequence of increasing gradients for the regression lines as one moves to sites further from the coast. This may be because the gauge is situated on a ridge to the north of the main line of gauges, where the slope up from the coast is significantly steeper.

Case study 2: 16 December 1984

Data for this event are shown in the usual way in Fig. 4 and Table 4. December 16 brought thunderstorms, record rainfalls, and flooding to Auckland City. Fed by a strong northwesterly flow, the thunderstorms accompanying a low brought rather less rain (about 20 mm in 36 h) to the Waitakere Ranges. Average intensities recorded by the gauges were significantly

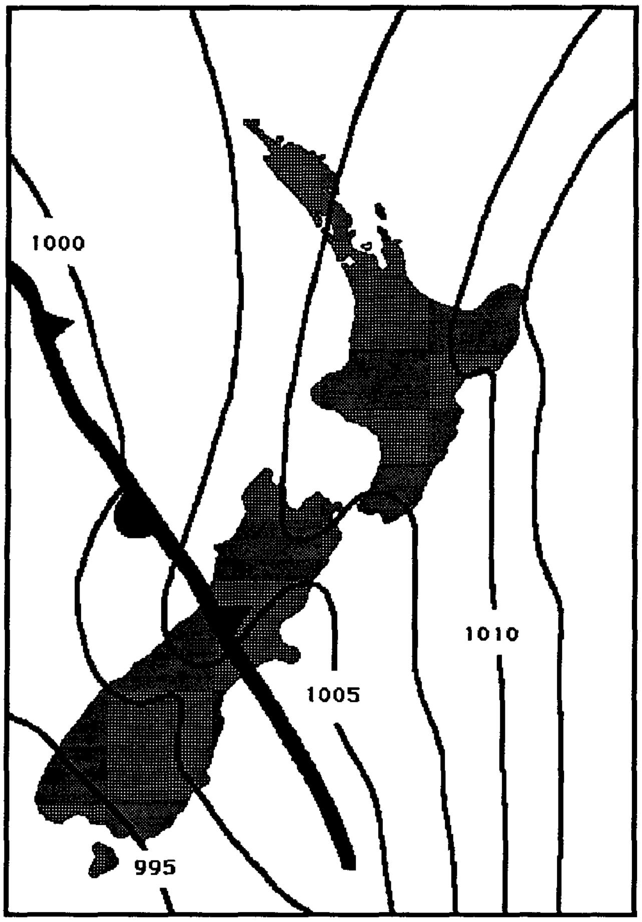

Fig. 5 Case study 3. The surface synoptic chart for 0000 NZST on 21 December 1984.

Table 4 Case study 2. Total gauge catches and the number of 512 s sample periods during which the mean rainfall exceeded a given threshold. The wind was parallel to the hill range.

Gauge no.	Total catch (mm)	Thresholds (mm/h)				
		0.1	1	2.5	5	10
10	18	76	53	9	1	0
14	15	91	43	16	6	1
8	20	101	55	18	5	0
6	25	93	46	25	4	3
5	20	84	43	17	4	1
4	20	110	46	26	4	1

less than for case study 1. No clear pattern of rainfall enhancement is evident in relation to the hill profile, and neighbouring gauges show marked differences in rainfall pattern. These observations are consistent with the presence of strong convection and of convection cells that are small in comparison with the horizontal scale of the gauge network. In addition, the low-level airflow was more or less parallel with the hill range, so that little topographical effect should be observed. The same gauges were in operation as for case study 1.

Case study 3: 21 December 1984

The surface synoptic conditions are shown in Fig. 5, with rainfall being caused by a front moving in from the southwest.

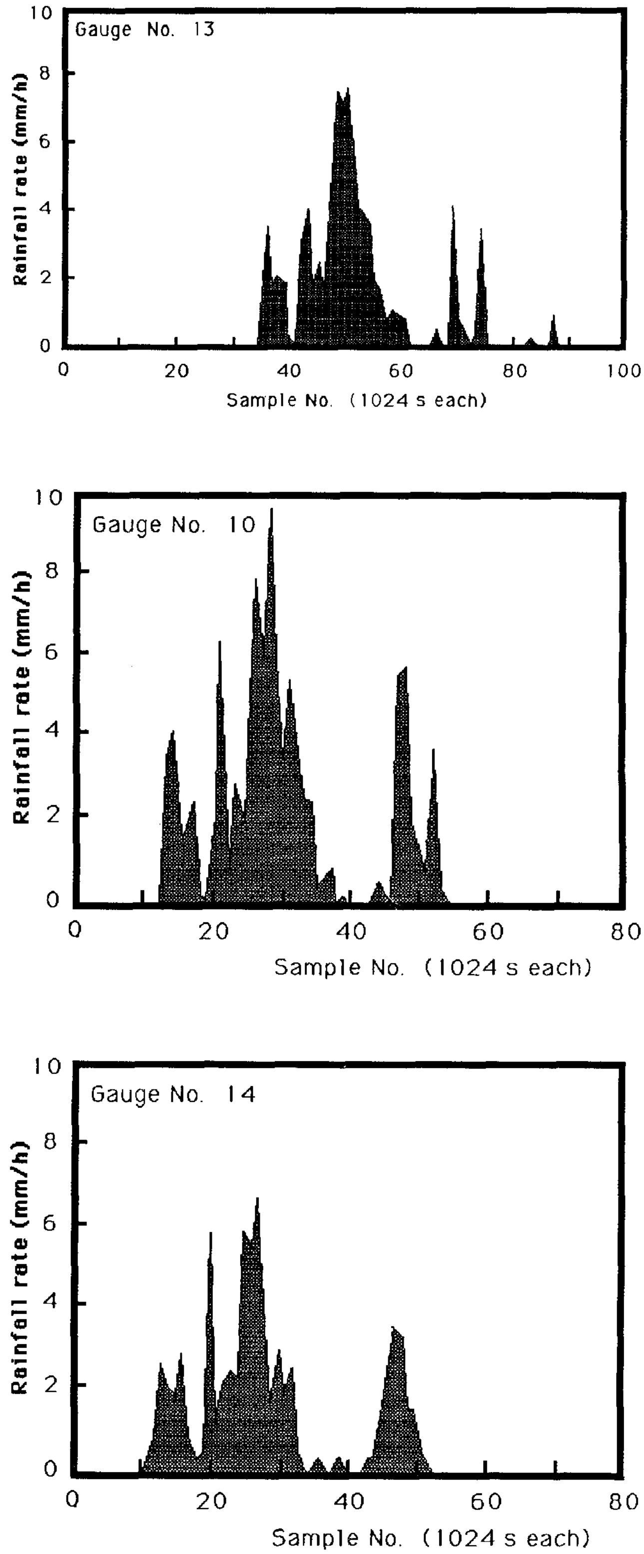

Fig. 6 Case study 3. The rainfall intensity records for the event, using a sample period of 1024 s.

The mean low-level wind was 4.4 m/s, slightly less than for case 1, from the ENE, so that the gauge array was again on the lee side of the hill; the upper level wind was a northwesterly of 9 m/s. The surface front was not as well defined as that for case 1, and during its passage the surface wind backed only a little to become a northerly. Rain fell for about 12 h from 7 p.m.,

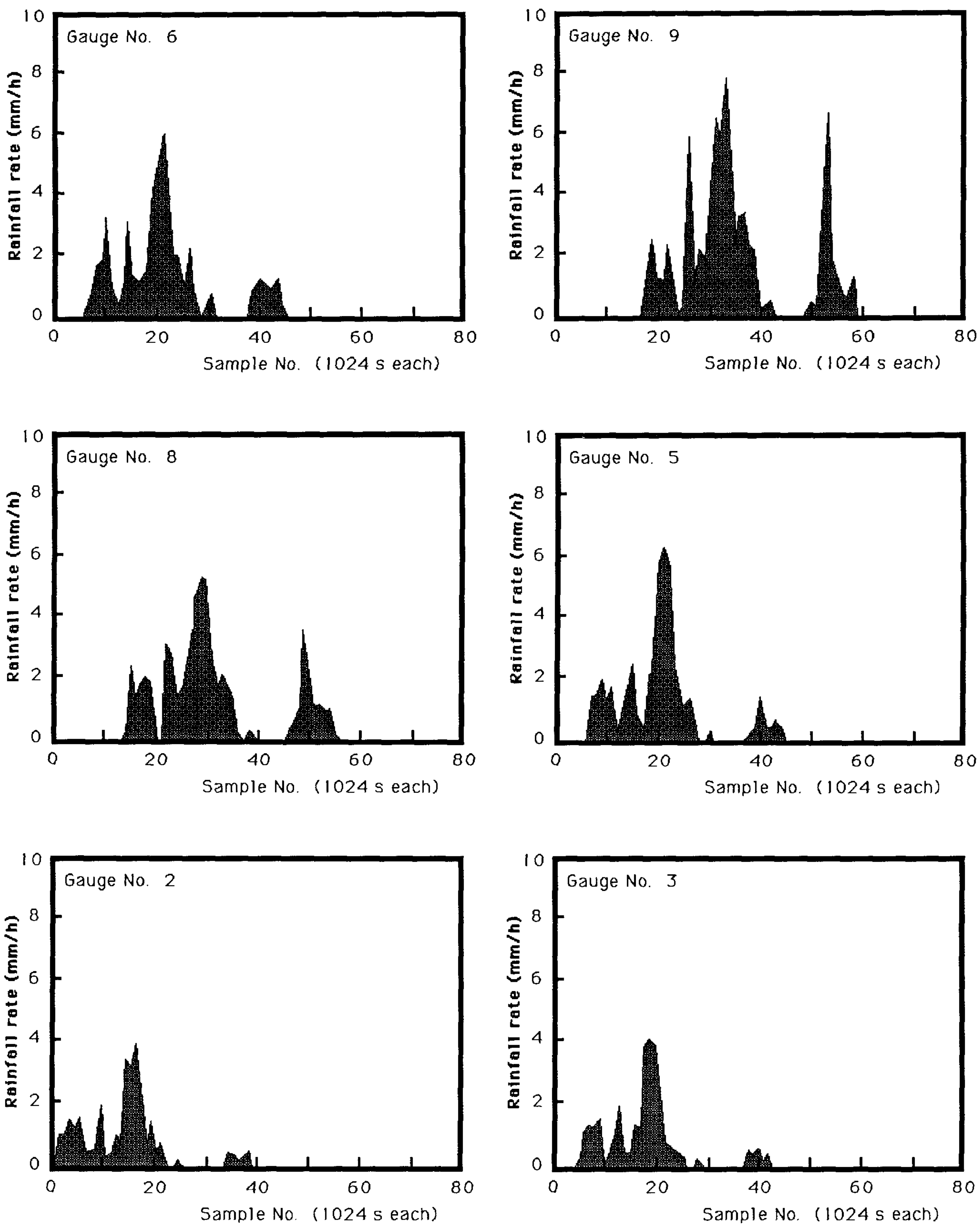

Fig. 6 *(continued).*

reaching a maximum of about 8–10 mm/h (1024 s sample time) at 11.30 p.m. Nine gauges were in operation, namely, gauges 2, 3, 5, 6, 8, 9, 10, 13, and 14. Of these, all but gauges 3, 9, and 14 lay on the main array line. Gauges 9 and 14 provide a good mid-hill check on the lateral variability of the storm, and should not show very large variations from the record for gauge 8, despite large differences in site altitude. Figure 6 shows the individual raingauge records during the rainfall event, and the records for gauges 8, 9, and 14 are reasonably similar though by no means identical. Rainfall catch data are shown in Table 5, and least-squares regression results are shown in Table 6.

In this case study, the greatest catch was at gauge 10, and all other data were consistent with this finding. The pattern of enhancement along the gauge array was very similar to that found in case study 1. Furthermore, the data of Table 6 show high correlation coefficients, suggesting good linearity in the relationship betweeen rainfall enhancement and rainfall rate. The catch at the coast of 31% with respect to gauge 10 compares closely with the value of 35% with respect to gauge 14 that was observed in the first case study for the leeward situation. In the present study, the gradient of the regression line and the sample count above the 5 mm/h threshold for gauge 9 deviate significantly from the values for gauges 8 and 14 on this occasion. Although all three gauges lie at the same distance from the coast, it is possible that the anomalous enhancement of gauge 9 is an effect of the ridge which lies to the north and east of the gauge site. With respect to this ridge, gauge 9 lies on the lee side and about 1 km downward of the ridge in a position close to that predicted for a maximum by the model of Carruthers & Choularton (1983).

Table 5 Case study 3. Total gauge catches and the number of 512 s sample periods during which the mean rainfall exceeded a given threshold. The array was to the leeward side of the hills.

Gauge no.	Total catch (mm)	Thresholds (mm/h) 0.1	1	2.5	5	10
13	26	31	24	14	4	0
10	31	36	24	18	9	0
14	22	36	23	11	4	0
9	25	35	24	11	6	0
8	19	35	24	10	2	0
6	16	31	21	6	2	0
5	14	29	17	5	3	0
3	10	26	12	3	0	0

Table 6 Regression analysis of raingauge records, using gauge 10 as the reference gauge, for case study 3. The gradient corresponds to the gauge catch ratio over all rainfall intensities. The correlation coefficient is a measure of the independence of gauge catch ratio from rainfall intensity.

Gauge no.	Correlation	Gradient
13	0.92	0.93
14	0.91	0.66
9	0.95	0.89
8	0.87	0.68
6	0.86	0.48
5	0.82	0.47
2	0.84	0.31

Table 7 Case study 4. Total gauge catches and the number of 512 s sample periods during which the mean rainfall exceeded a given threshold.

Gauge no.	Total catch (mm)	Thresholds (mm/h) 0.1	1	2.5	5	10
14	43	64	49	25	3	0
8	36	64	46	17	1	0
6	39	58	46	21	2	0
5	45	58	45	27	8	0
2	37	56	45	20	4	0
3	38	58	37	4	0	0

Case study 4: 2 January 1985

The cold front producing rain during this case study was associated with an easterly wind at the surface of rather less than 4 m/s, which eased to calm conditions. The upper wind was always <7 m/s from the northwest. Figure 7 shows the rainfall records obtained from gauges 2, 3, 5, 6, 8, and 14, and Table 7 gives details of the total catches and of sample distributions. Although a total of 20 h of rainfall was experienced and total catches exceeded those of case study 3, no systematic pattern of rainfall enhancement in relation to distance from the coast or in relation to any other orographic features could be discerned. Any differences in gauge records were sufficiently small that they could reasonably be attributed to the asynchronous nature of the network. It would appear that this lack of pattern can be attributed to the lower windspeeds, which were insufficient to form the low-level clouds associated with the Waitakere Ranges into an organised system. As a result, the topography of the hills had little or no influence on the distribution of rain.

CONCLUSIONS

A preliminary investigation of rainfall distribution over a raingauge array situated in the Waitakere Ranges of West Auckland during the passage of four cold fronts has revealed a systematic orographic influence on two occasions. The rainfall on these occasions increased substantially with distance from the coast, whether the gauge array was, by virtue of the low-level wind direction, on the lee side or windward side of the hills. In the former case (which occurred twice), the rainfall rate at the coast was only about 30–35% of that near the hilltop, and in the latter case, was of the order of 60%. Allowing for small-scale perturbations in the hill profile, a further conclusion is that the increase in rainfall rate was a monotonic function of distance from the coast. The above observations are consistent with the model, first proposed by Bergeron (1965), of rain enhancement caused by the passage of rain from widespread synoptic-scale systems through localised low-level clouds associated with airflow over low hills. The observations are also consistent with the predictions of the model of Carruthers & Choularton (1983), in particular with the nonsymmetric rainfall distribution revealed by the wind reversal in case study 1. However, in contradiction to their model and that of Storebo (1976), the present studies suggest strongly that rainfall rates at sites with different enhancements are linearly related. That is, the ratio of catches at two sites is fixed and independent of the rainfall intensity.

The lack of any clear pattern of rainfall enhancement in two case studies is attributed to separate causes. In case study 2, widespread instability and localised convection led to small-scale disturbed airflow at low levels. In case study 4, the low-level airflow was insufficient to give rise to effective feeder clouds over the Waitakere hills; the situation was probably even less conducive to orographic enhancement because of the comparatively low humidity of the airflow on this occasion. If the latter explanation is correct, it is consistent with the observations of Hill et al. (1981) that rainfall enhancement is

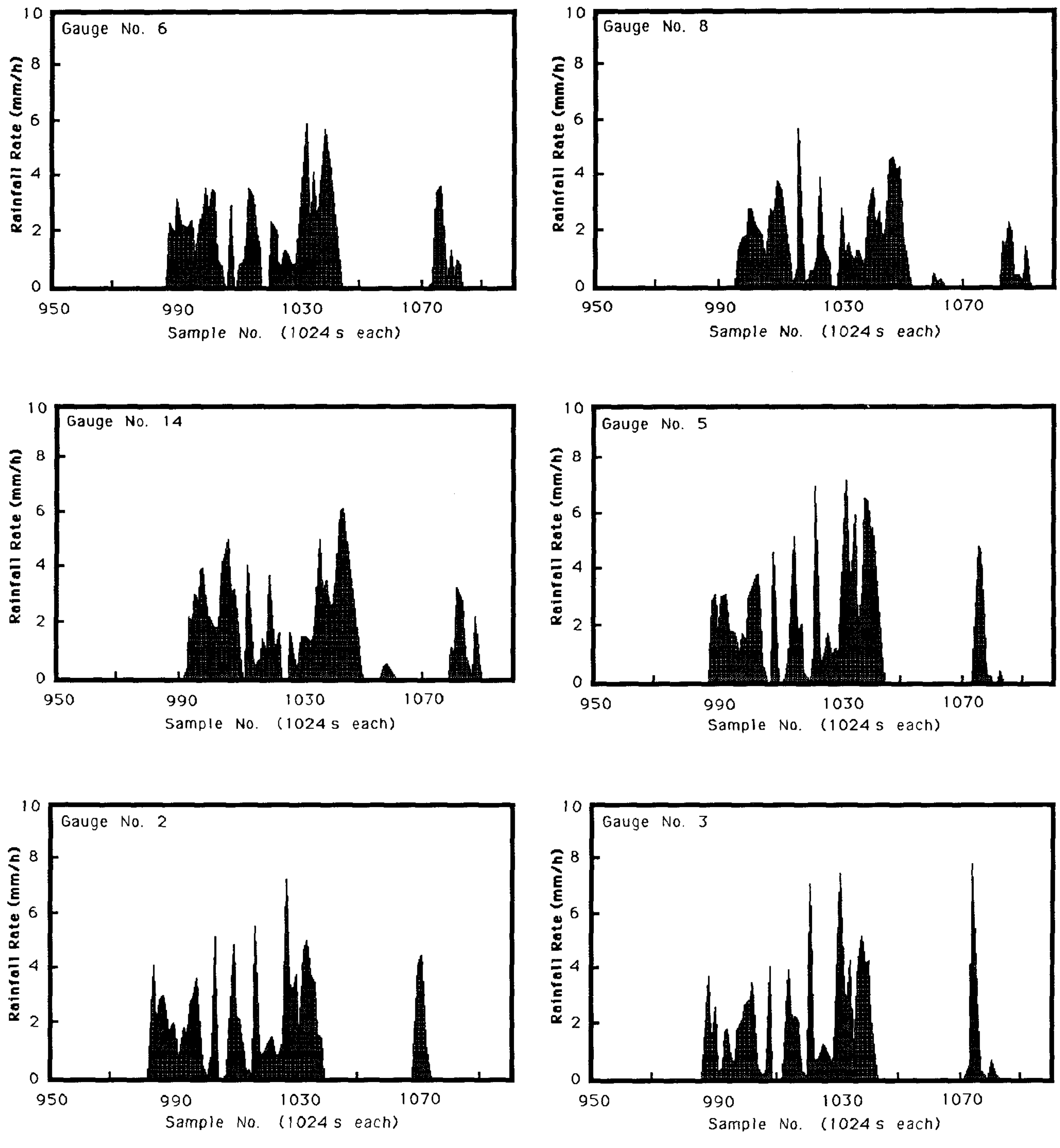

Fig. 7 Case study 4. The rainfall intensity records for the event, using a sample period of 1024 s.

strongly dependent on low-level windspeed, since appreciable enhancement was encountered at only slightly larger airspeeds in cases 1 and 3. This is in contradiction to the theoretical models, which predict only weak dependence of enhancement on low-level windspeed.

The preliminary results are encouraging, but further work is required to quantify the dependence of rainfall enhancement on low-level windspeed and seeder (upper level) rainfall rate. The lack of local balloon soundings precluded a full analysis of the conditions prevailing before and after a cold-front passage, and limited data-storage space required sample periods longer than is desirable. Some raingauges malfunctioned for trivial reasons. Further work is planned, and the raingauge design has been considerably improved, enabling sample times as little as 15 s to be used, as appropriate. Shorter sampling times, used in conjunction with a dense gauge network, will enable finer structures in rainfall to be examined. An extension of the present work has been the simultaneous observation of rainfall at two sites of different orography on the west coast separated by a distance of about 20 km.

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