NEW ZEALAND METEOROLOGICAL SERVICE

TECHNICAL INFORMATION CIRCULAR NO. 169

SEVERE DAMAGE TO FORESTS IN CANTERBURY, NEW ZEALAND, RESULTING FROM OROGRAPHICALLY REINFORCED WINDS

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This paper was presented by Mr H.W. Hill at the W.M.O. Symposium on Forest Meteorology held at Ottawa, Canada in August 1978 and will be published in the Conference Proceedings.

It is issued for the information of staff.

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30 March 1979

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ABSTRACT

During the last 50 years large areas of exotic softwood forest, predominantly pinus radiata and pinus nigra, have been planted in New Zealand. About 30 000 ha of such forest is located in Canterbury, an eastern district of the South Island and this is largely in four major forests ranging from 4000 to 8000 ha. These forests are located on the lowlands between the Southern Alps and the eastern coast. Within the last decade or so the earlier plantings have reached maturity with a height of 20 m or more.

The inland area of Canterbury in which these forests are located is prone to occasional very severe northwest winds in which orographic augmentation is a significant factor. Evidence for the relatively short history of the mature stands in these forests suggests that once or twice in a decade severe wind damage can be expected. Such an event occurred on 1 August 1975, when in one of the forests with an area of 7000 ha, 1096 ha of mature stands were completely flattened - an estimated volume of 300 000 m^3 of timber. There was also severe damage to 370 ha of smaller second rotation stands. Appreciable damage also occurred in two of the other major forests.

This case is examined in some detail, on the several scales from the synoptic through the mountain-flow regime to the scale of the flow over the forests themselves.

INTRODUCTION

During the last 50 years large areas of exotic softwood forests have been planted in New Zealand and in 1976 there were about 730 000 ha of production forest of this type in the country. About half of this is in the northern half of the North Island, but there are appreciable areas in other parts of the country. The trees in use are nearly all pines with pinus radiata being the predominant species and now comprising over 80 percent of the total. There are also some appreciable areas of pinus nigra and smaller amounts of other types. This paper is concerned with the exotic forests in the eastern area of the South Island known as Canterbury, where there are over 30 000 ha of such production forests largely in the hands of the New Zealand Forest Service, but another 14 000 ha in smaller lots divided between some local authorities and private owners. Most of the earlier planting of these forests was begun in the 1920's and in the growing conditions of Canterbury pinus radiata is approaching maturity at about 30 years by which time this species has grown to a height of 20 m or more. There is therefore only a relatively short period of one to two decades with any appreciable number of mature trees and on a climatological scale this may be rather short to be objective with statements, for example, on the risks from wind damage as an economic factor.

There have, however, been three very significant wind storms in recent times, all of them northwesterly which as will be seen later involves a major orographic flow problem. These were as follows:

13 July 1945, which damaged severely 1400 ha in Balmoral Forest.

22 March 1964, which caused wind throw of 4050 ha at Eyrewell.

1 August 1975, which caused widespread damage throughout most of the Canterbury forests and the details of which are given later.

While these three severe northwesterly storms are outstanding there have been a number of less severe events which have caused significant but not comparable damage. While the northwesterly storms are by far the most important there are on record severe winds from other directions. Of these a southwesterly storm on 10 April 1968 is probably the most important but only damaged 200 ha in one of the main forests, Ashley.

THE MAIN CANTERBURY FORESTS - LOCATION AND SOILS

There are four major production forests of exotic pines in Canterbury, all in the hands of the New Zealand Forest Service, which is a state department. They are:

Eyrewell	7000 ha
Ashley	6000 ha
Balmoral	8000 ha
Hanmer	4000 ha

The areas are given in round figures all of which may not necessarily be in production on a given date.

Their locations are shown in Fig. 2 which also includes the main features of the topography and a few other places named in the text. Each forest is situated fairly close to the eastern foothills of the Southern Alps, the major mountain system which runs nearly southwest to northeast much of the length of the South Island. In general they lie within 10 to 15 km of these hills and some 30 to 40 km east of the high mountains which reach about 2000 m in this part. Two of the forests, Eyrewell and Balmoral, lie in the valleys of and adjacent to major rivers emerging from deep glaciated valleys in the ranges to the west. While this is probably significant in considering their relationship to the topography it also has an important bearing on the soil type on which they are located.

These rivers both have wide shingle fans and during the course of recent geological time have continued to cut down through their beds thus leaving wide lateral expanses of shingle resting on an impermeable layer. Subsequently, a shallow deposit of loess has covered the shingle thus producing a shallow stony soil on a hard impermeable base. The characteristic name of this soil in New Zealand is 'Lismore'. The Eyrewell and Balmoral Forests are thus planted on soil in which rooting is necessarily shallow and lateral with poor tap-root penetration. Under these circumstances in severe wind conditions the trees are toppled at the roots, often the whole root-plate being torn from the ground.

In contrast much of Ashley Forest and Hanmer Forest are on deeper silt loam soils in which root penetration to an appreciable depth is possible. In these forests while there is still some windthrow where uprooting occurs, a more appreciable part of the damage consists of shattering and breakage. The soil types have therefore considerable significance in the nature of the wind damage sustained.

THE CANTERBURY NORTHWESTERLIES

With the fairly frequent passage of depressions over the Southern Ocean to the south of New Zealand there are in the course of most years a number of occasions when a strong northwest to west flow in the lower atmosphere covers much of the southern Tasman Sea - New Zealand area. At Christchurch Airport in the period 1960 to 1972 inclusive there were on average about 56 hours per year with winds in the sector west-northwest to north-northwest of mean speed 13 m/s or more and 5 hours per year with winds in this sector exceeding 17 m/s. In view of the orographic wave pattern in the northwest flow strong northwesterly winds occur much more frequently in inland areas of Canterbury than in areas close to the coast such as Christchurch.

In many strong northwesterlies a separation pattern develops at the mountain tops. In the upper branch of the flow there is usually an extensive arch cloud developed with lenticular bands with fairly short standing waves of a few km to tens of km appearing within it. The descending foehn part of the flow also has a wave pattern which appears as a complex distribution of the surface winds. It seems however from time to time in strong flows in a very deep thermally stable layer a very long orographic wave as distinct from the more common lee waves appears. In the more common case it is usually inland in the areas just east of the foothills that the strong northwesterly surface winds occur while as little as 30 km away at Christchurch Airport or on the coast the winds remain light and variable for long periods, or moderate northeasterly. With fluctuations in the flow incident onto the west of the South Island the northwesterly winds from time to time appear at the coast. In the very long orographic wave pattern northwesterly winds of great strength can affect all the plains and the areas seaward of the east coast. The case of 1 August 1975 is fairly obviously of the latter type.

THE GREAT NORTHWESTERLY STORM OF 1 AUGUST 1975

Of the three very significant cases of severe northwest winds which caused extensive damage to forests, 1945, 1964 and 1975, the August 1975 storm is outstanding for the widespread nature of the destruction, all four major state production forests being badly affected together with other smaller plantations. Some idea of the scale of damage can be seen in the following table for the four main forests.

	Area windthrown	Damage as percentage of area stocked
Eyrewell	1767 ha	34.5
Ashley	700 ha	12.6
Balmoral	3323 ha	43.0
Hanmer	273 ha	7.3

Through all Canterbury it is estimated that a total of 2.2 million cubic metres of timber, as sawlog volume, was windthrown. Of this to date, as the result of a large scale operation, about 1.2 million m^3 has been salvaged. It is apparent that much of the damage occured to mature stands and the 1767 ha at Eyrewell, as an example, was made up of almost

1100 ha of mature trees having a height exceeding 20 m, while a further 370 ha consisted of somewhat smaller trees of a second rotation.

THE SYNOPTIC SCALE ASPECTS OF THE 1 AUGUST 1975 STORM

In the day or two preceding 31 July 1975 a complex family of depressions covered the area south of the Great Australian Bight while a relatively intense anticyclone lay over the northern parts of the Tasman Sea and New Zealand. By 1200 NZST (all times subsequently referred to are NZST) 31 July (Fig. 3) a depression with central pressure below 965 mb had moved into the area south of New Zealand and a strong northwesterly airstream covered much of the southern Tasman Sea and southern New Zealand on the lower latitude side of an active cold front. At this stage the strength of the flow was already reflected in the large pressure gradient of about 20 mb in 200 km along the southwestern coasts of the South Island and in an orographically derived gradient of about 14 mb from west to east across the island. Under these circumstances a strong northwesterly flow had already spread to some parts of the eastern coasts with the mean surface winds reaching 10 to 15 m/s and by 1400 hr 31 July the anemometer at Eyrewell Forest was recording a mean wind of over 20 m/s with many gusts over 30 m/s (Fig. 4D). This wind was strong enough to cause some minor damage, e.g. to break some branches. By 1600 NZST it was however decreasing again falling to an average of 10 m/s for some hours. This transitory period of strong northwesterlies developed soon after a significant increase to 30 m/s occurred as low as 1.5 km in the Christchurch Airport radar wind soundings and presumably resulted from a period when the strong flow was brought to the ground in the orographic wave development. These few hours of fairly strong winds may have caused some initial loosening of the shallow-rooted trees rendering them more susceptible to damage in the very much stronger winds that were to follow 12 hours later.

At midnight 31 July/1 August the cold front lay close to the southern coast of the South Island preceded by very strong northwesterly flow over the South Island and by 0600 hr 1 August lay across the southern areas of the South Island (Fig. 5), continuing to move northeast to reach Christchurch about midday.

THE PRE-FRONTAL VERTICAL WIND STRUCTURE

Vertical wind speed profiles from the ground to 15 km for Invercargill on the south coast of the South Island and for Christchurch are shown in Figs 6 and 7, covering the period from 0000 NZST 31 July to 0600 hr 1 August. These are radar-measured winds at six-hourly intervals. The wind directions in tens of degrees from north (36) are also indicated. The first three soundings from Invercargill (Fig. 6) show a fairly uniform gradient of velocity in the vertical from the ground to about 3 km, at which height there was an increase with time from 35 m/s to over 45 m/s. Above 3 km there was little gradient of velocity until the high tropospheric jet stream was reached above 12 km. In the second set of profiles for Invercargill the rapid increase of the wind with height is again apparent. At 1800 hr 31 July a very low level wind maximum exceeding 40 m/s was reached between 0.5 and 1 km with a second maximum of nearly 50 m/s at 2.5 km. At 0000 hr 1 August there was again a large increase of the wind with height to reach 40 m/s at 2 km above which the speed changed little until the high tropospheric maximum was reached around 12 km. The five profiles up till this last time show the progressive veering of the wind with the approach of the frontal trough. The final sounding at 0600 NZST 1 August was post-frontal and shows a marked decrease in the speeds in the 1 to 3 km layer and the appearance of the high tropospheric jet stream reaching over 55 m/s around 9 km.

It appears from these Invercargill wind soundings that ahead of the surface cold front there was a very strong low level jet stream possibly comparable with that described by Browning and Pardoe (1973). In the first three soundings when the flow, except very near the ground was only west to west-northwest, it is reasonable to suppose it represented the undisturbed flow preceding the front. As the flow turned more northwesterly the effects of the orographic wave pattern would become increasingly important and the higher speeds at very low altitudes, especially that seen at 1800 hr 31 July would support this.

The sequence of vertical wind profiles for Christchurch is shown in Fig. 7. As might be expected the Christchurch winds at 0000 hr and 0600 hr do not exhibit the same large velocity gradient as those at Invercargill at the same time, Christchurch being about 400 km further away from the advancing front. However, at 1200 hr 31 July there was an appreciable increase of wind at the ground and the appearance of a low level maximum of 30 m/s at 1.5 km and this will be seen associated with the redistribution of the pressure gradient across the South Island (Fig. 9) discussed in a following section. Above the low level maximum the wind regime was fairly uniform until the jet stream was reached at about 12 km. It will be seen however that between 0000 NZST and 1200 hr 31 July there was a significant change in the wind direction above about 5 km from southwest to somewhat north of west. The subsequent Christchurch soundings at 1800 hr 31 July and 0000 hr 1 August show low level wind maxima at 2.5 and 3 km respectively, the latter nearly 40 m/s with direction west or slightly north of west. At 0600 NZST 1 August there was a maximum of 47 m/s, west-northwesterly, at only 2 km. It was in the few hours just prior to and around this time that the major damage occurred.

The wind soundings have demonstrated the presence of a very strong low level wind maximum. The Christchurch temperature sounding for midday 31 July (Fig. 8) in the pre-frontal northwest flow shows large thermal stability up to nearly 3 km or above the mountain tops. In the flow upstream of the South Island, i.e. over the Tasman Sea the satellite pictures showed low top closed-cell cloud confirming the stability in the lower atmosphere. Conditions were therefore similar to those described by Klemp and Lilly (1975) who dealt with severe winds in the lee of the ranges at Boulder, Colorado, conditions being favourable for a large amplitude mountain wave becoming established over the South Island.

THE EFFECTS OF THE WAVE ON THE SURFACE WIND REGIME

The effects of the descending motion in the lower atmosphere in the mountain wave pattern can readily be seen in the sequence of anemograms from stations along or near the eastern coasts and these are shown for Taiaroa Heads, a coastal station just northeast of Dunedin (Fig. 4A), for Timaru Airport (Fig. 4B), and Christchurch Airport (Fig. 4C), and for the inland station, Eyrewell Forest (Fig. 4D). At Taiaroa Heads there was a very steep rise in the surface wind speed from about 0330 hr with sustained mean maximum wind of about 35 m/s with many gusts which went off the top of the chart at 45 m/s between 0345 and 0515 hr. At Timaru Airport which is about 140 km further north, a similar maximum wind period occurred between 0330 and 0415, or nearly simultaneously with Taiaroa Heads. There is no reason to doubt the timing of these anemometer charts as the events were confirmed by plain language remarks with the succeeding observations. At the southernmost of the four main forests, Eyrewell, which has a recording anemometer, there had been several periods through the night in which the mean wind speed rose to over 15 m/s, with gusts to 30 m/s soon after 0200 NZST. Soon after 0400 NZST there was a rapid increase in the wind speed and by 0430 gusts were exceeding 45 m/s at which time power lines failed and the record ended. This point on the chart is well established by the time at which the electric clocks at the forest headquarters stopped, and it is known that at that time widespread damage was occurring in the forest. Eyrewell lies about 130 km north of Timaru but is about 35 km from the coast. Although Christchurch Airport is only 20 km from Eyrewell the steep rise in the wind speed did not occur there until after 0600 with the maximum mean speed and the highest gusts (over 45 m/s) occurring about 0730. The propagation of the mountain wave bringing the very high speed air to the ground was thus quite slow, only about 10 km/hr.

In inland areas much closer to the high mountains the northwest wind was blowing quite strongly most of the time from 1200 hr 31 July till 1100 1 August. This is shown for example at the Mount Cook airstrip (Fig. 4E) where there was a nearly constant mean wind of 15 to 20 m/s with gusts frequently exceeding 30 m/s but nothing resembling the periods with a great rise in the wind speed of appreciable duration seen in the other records just cited. This station is at the foot of the Tasman Glacier very close in the lee of the highest part of the Alps where a number of peaks well exceed 3000 m.

THE ASSOCIATED SEA LEVEL PRESSURE FIELD

The effects of the orography on the wind flow are reflected in the pressure field. Fig. 9 shows the barograph traces for Wellington, Christchurch and Invercargill which reflect the north-south component of the pressure gradient, and Hokitika, Lake Coleridge, Christchurch which indicate the west to east component. All the stations show the general pressure fall ahead of the advancing cold front. After about 2000 hr 30 July the north-south component (Kelburn minus Invercargill) became large and remained fairly uniformly so through most of the period of the diagram reaching a maximum between 2000 hr 31 July and 0400 hr 1 August.

The Wellington to Christchurch pressure difference reached a maximum about 0600 1 August, near the time of the very severe winds in the Eyrewell - Christchurch area.

The effects of the orography are clearly seen in the large west to east component of the gradient developed between Hokitika and Christchurch. It increased to 12 to 14 mb from about 0400 hr 30 July remaining fairly close to these values most of the period except for a time around 0600-0700 hr 1 August when it exceeded 16 mb. Hence strong pressure gradients in both north-south and west-east directions existed for a very long period, much longer than the few hours of the destructive winds. The Mount Cook airfield, close into the high mountains had strong but not destructive winds most of the long period. The effects of the orographic wave pattern on the pressure field can be seen when the barogram for Lake Coleridge is also examined. With this additional station about midway between the west and east coasts the redistribution of the gradient across the Island is seen. There was a period after 0600 NZST 31 July when the pressure gradient eastward of the Southern Alps increased to about 6 mb and this presumably corresponds to the increase in the low level winds when 30 m/s at 1.5 km was reached at 1200 hr. A further more significant redistribution of this gradient occurred from about 0200 1 August from which time much of the greater part of the gradient across the South Island lay between Lake

Coleridge and Christchurch reaching 10 to 14 mb in about 65 km between 0400 and 0800 hr, the time of the destructive winds. The very marked oscillation seen on the Lake Coleridge barogram about 0200 1 August probably represents a significant change in the orographic wave regime which preceded this pressure gradient redistribution.

It thus appears that there was quite a broad area ahead of the cold front in which the flow was very strong and the potential for very strong winds to develop at the ground was there for many hours. The much more limited period of the very severe winds at the ground seems then to be related to the orographic wave.

THE WIND REGIME ON THE SCALE OF THE INDIVIDUAL FOREST AND ITS EFFECTS

As an example the Eyrewell Forest is examined, althouth many of the comments here would also apply to the other forests, especially the Balmoral Forest with a somewhat similar river valley location. The Eyrewell Forest and its environs are shown in Fig. 10. The Forest is about 20 km long, nearly west to east and about 5 km across at its widest parts. Lying adjacent to the Waimakariri River it is located on the stony Lismore soils. From the nearest point to the northwest where the Alpine foothills rise steeply from the plain to the northwest edge of the Forest is rather more than 10 km. The intervening countryside is a generally level, gently sloping plain which in August (winter) would be in short grass or fallow and sometimes, but not on this occasion, snow covered. A few shelter belts, mostly pines lie on the margins of some of the fields, but apart from these the terrain would be aerodynamically fairly smooth.

Northwesterlies of any appreciable strength arrive on the plains with considerable turbulence. The descending foehn flow, especially in conditions of strong vertical shear, develops wake vortices over the ridge tops and these eddies are carried down in the flow. The shear zone between the fast descending foehn flow and the air emerging from the adjacent valley also constitutes a vortex sheet. The effects of the turbulence can often be seen in the swirling clouds of particulates picked up from dry areas along the river beds in particular, and elsewhere over the plains in arid conditions, when there is much loose, dry, fine soil. In winds of the strength of this August case the turbulence in the wind passing over the plains was great and it is readily seen in the gustiness of the anemograms, Figs 4A-E.

While the northwest winds would have arrived at the forest edge already turbulent, the flow over the aerodynamically rough forest would inevitably enhance the disturbed flow and the pattern and scale of the destruction would seem to show this.

As is often the case there were areas in which the edge trees were left standing while much greater windthrow occured to leeward within the stands. This points to the increasing turbulence over the rough canopy and Papesch 1974 shows that there is a change of regime over a forest with the larger part of the stress on the windward edge being derived from the mean flow and an increasing amount to leeward from the turbulent eddies. This effect is further enhanced if not only is there the rough canopy but there are also clear areas within the forest of an appreciably different roughness length from that of the canopy. Under such conditions the power spectrum of the turbulence is changed. This probably leads to the turbulence having components with which trees of an increasing range of size are resonant, thus increasing the risk to the downwind stands. It is well known that opening areas in a forest for fire-breaks or by clear-felling can have serious consequences in an ensuing severe wind. It seems highly likely that the pattern of events in a severe storm such as this discussed here is that the edge trees start the enhancement of the turbulence while largely themselves remaining intact. As a consequence, trees downwind within the stand are windthrown thus opening clearings which then contribute to the turbulence spectrum and result in more damaging effects further to leeward. This seems very likely the case in the Eyrewell Forest where tall mature stands on the southern edge of the Forest suffered much of the severe damage. The increasing turbulence down stream over the forest probably implies also that there is a lowering of the zero plane, and a greater depth of the canopy becomes subjected to the strong turbulent flow. The tendency for the mature trees to suffer disproportionate damage is probably a feature of their structure, being not only crown-heavy but also having much more rigid branches. The effects of the aerodynamics of flow over the forest and the resultant damage is highlighted by the effects of the storm on shelter-belts on the adjacent plain. Most of these survived the storm reasonably intact suffering mostly only broken branches. The trees in these shelter belts were largely the same size, age and species as the large mature trees in the forest stands which sustained catastrophic damage.

DISCUSSION

The great northwesterly storm of 1 August 1975 appears outstanding not only for the great strength of the winds but also for the very widespread distribution of the severe winds. In the great storms of 1945 and 1964, while a great amount of damage was done it was largely restricted to one individual forest in each case. In this storm there was major damage to the four main production forests and many other plantations as well, spread over a distance of at least 300 km.

In any year there are invariably a number of periods when the orographically enhanced northwesterlies are significantly strong especially in inland areas east of the Southern Alps, but the return period of very damaging winds in individual forests would seem to be of the order of about 10 years. Storms of the severity and extent of the 1975 event must have a much longer return period, possibly of an order of magnitude more. From the practical aspect of forestry there is however a considerable economic significance attached to even one major storm in one forest in ten years and measures to minimise damage are desirable.

Forest management in areas prone to the occasional severe wind storm must take account of aerodynamic and silvicultural aspects. One problem must be the removal of timber and the clear-felling of areas within the stands which inevitably must be done in a production forest as from the aerodynamic aspect the increasing turbulence associated with changing the roughness length produced by clearings is well known to increase the hazards.

In the case of the forests on the shallow stony Lismore soil, thought has been given to deep-ripping of the soil before planting, in order to increase the depth of the root zone. The advantages of such attempts to ensure that the trees will remain standing in a storm of great severity are offset by the risk of having them shattered and broken and are in some ways questionable. It has proved easier to salvage the completely windthrown trees in the Eyrewell Forest as usable timber than the badly shattered logs, as for example in the Ashley Forest. There seems however to be some advantage in stimulating root and tree growth by fertilizer application as experience shows that in the early years of growth root penetration is improved by this means. Younger and more vigorously growing trees have proved more wind-resistant than old mature trees, with better resistance being found in the 15 to 25 year trees than in those of greater ages. It appears therefore that shorter-rotation-cropping is a possible solution to the problem.

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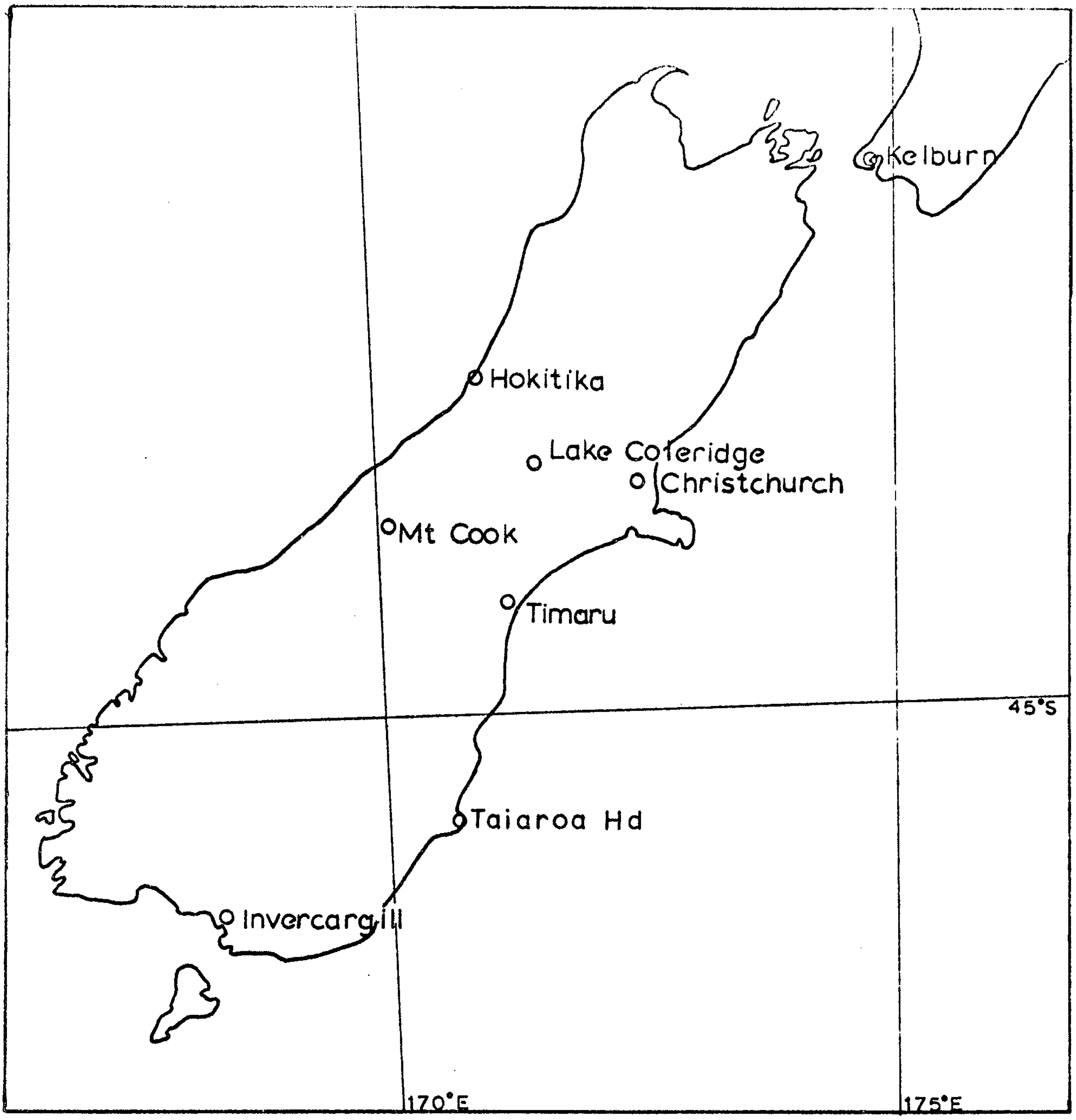

Fig. 1. Map showing places referred to in text.

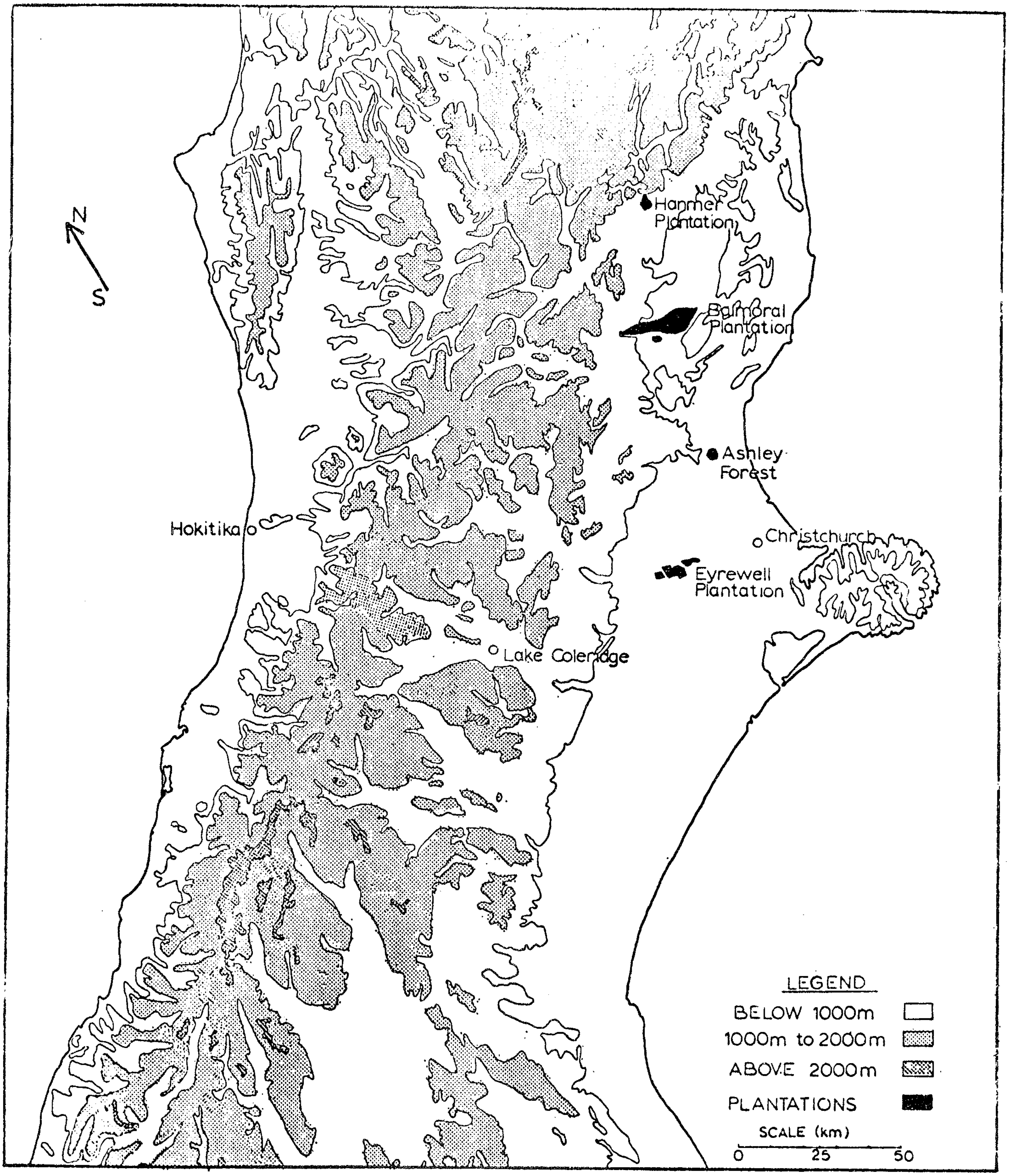

Fig. 2. Map showing the main production forests in the South Island, New Zealand.

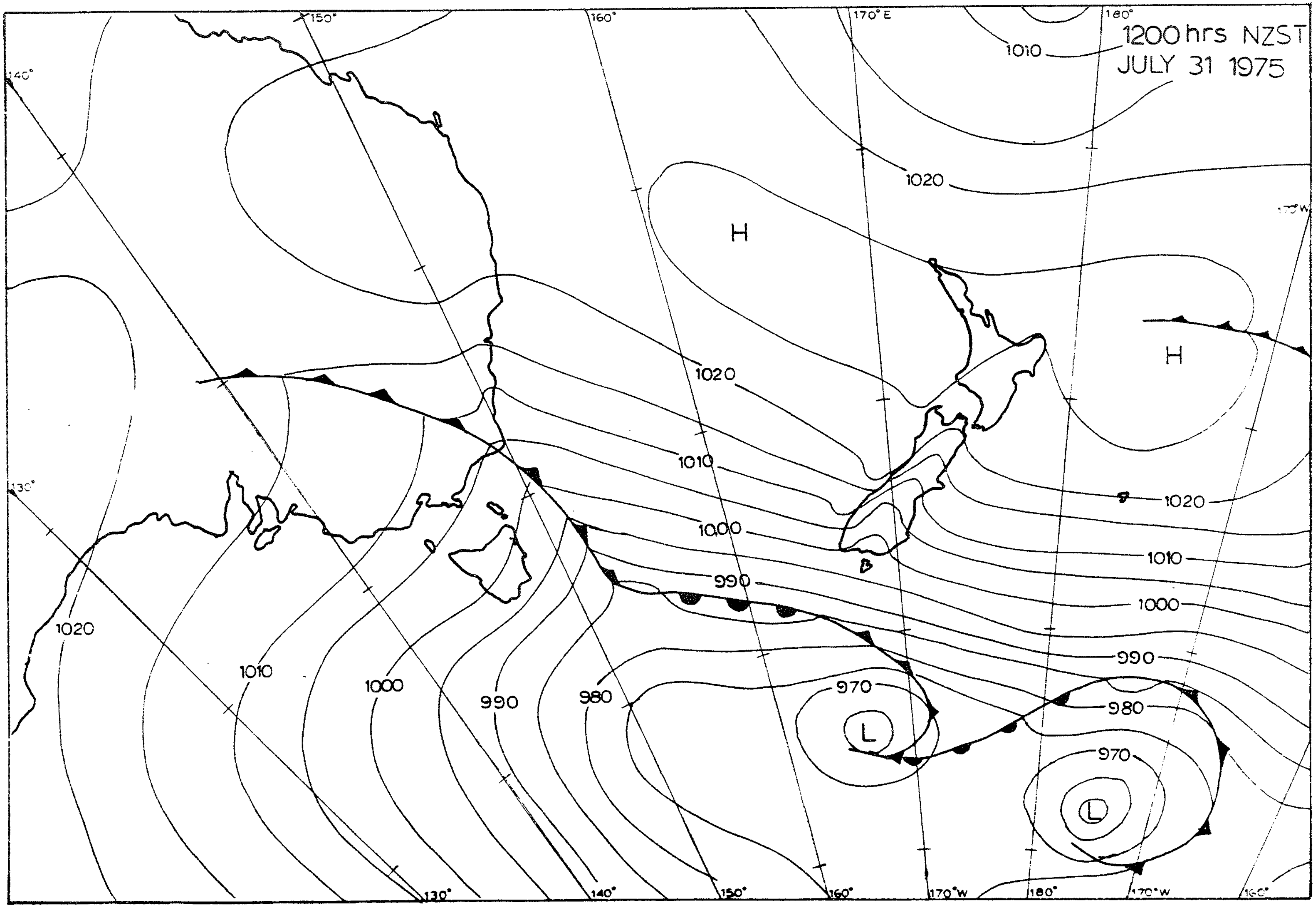

Fig. 3. Synoptic chart for 1200 NZST 31 July 1975.

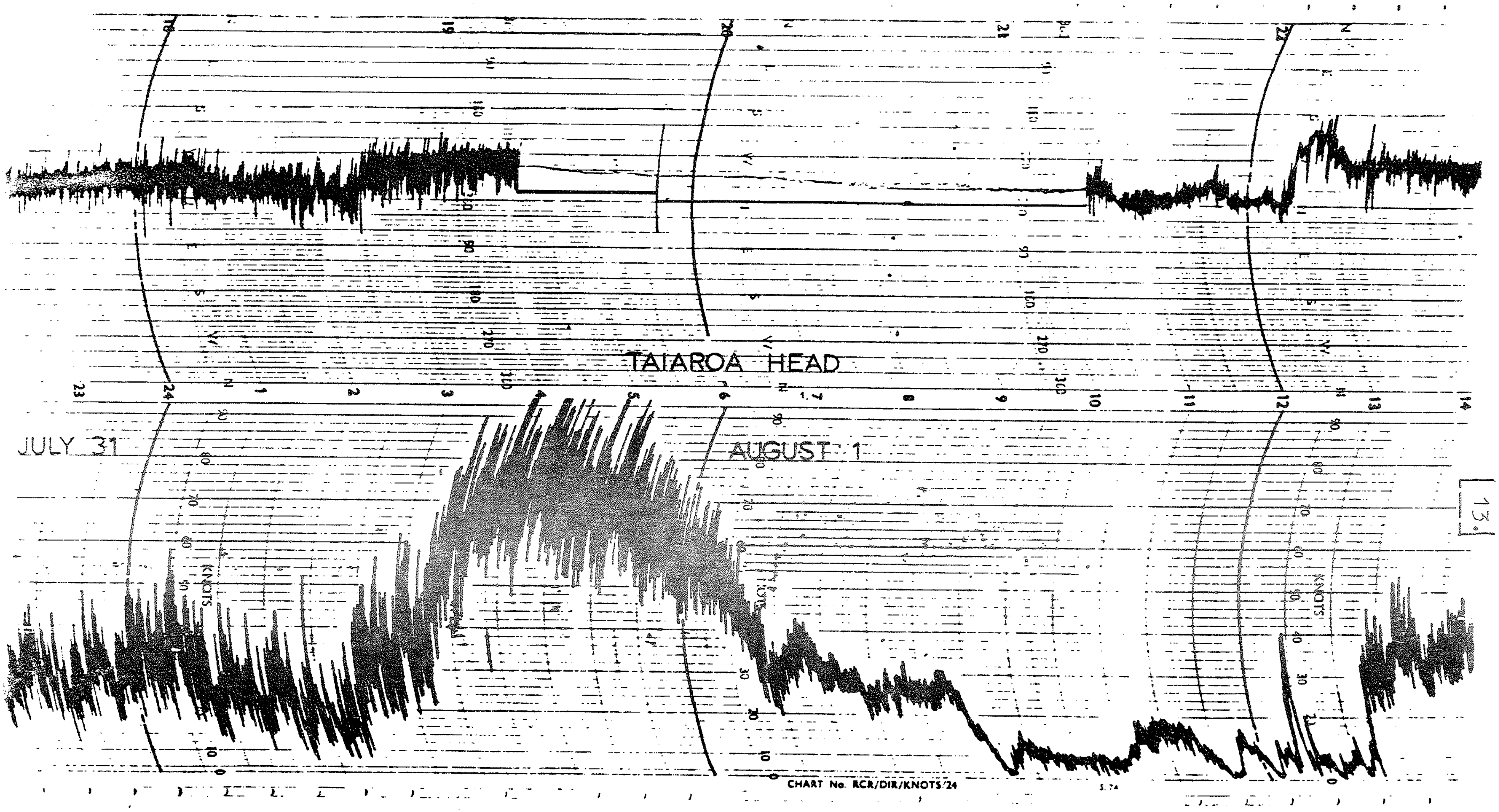

Fig. 4A. Anemometer charts, Taiaroa Heads.
Speed scale in knots (1 m/s = 2 kt).

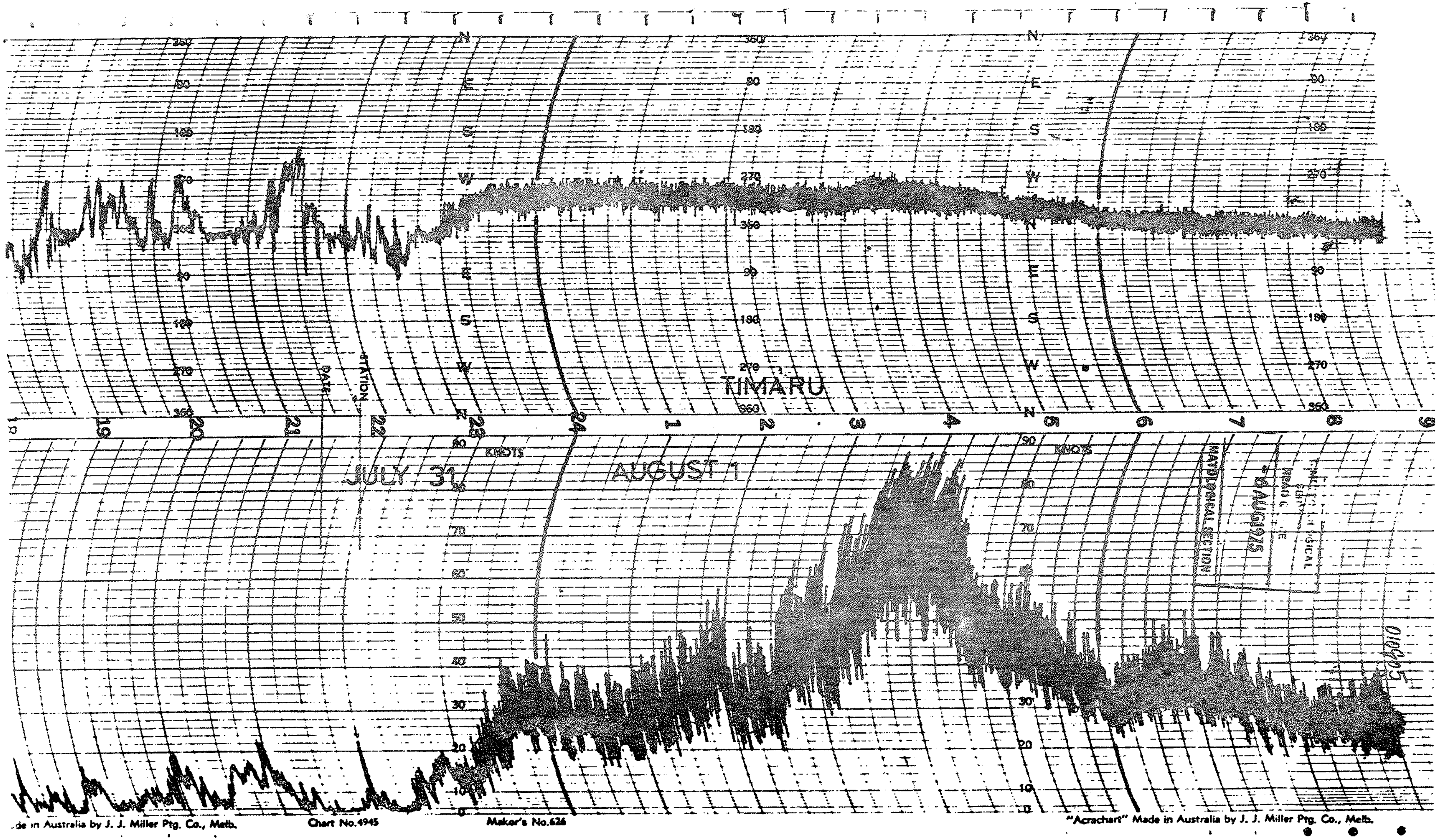

Fig. 4B. Anemometer charts, Timaru Airport.
Speed scale in knots (1 m/s = 2 kt).

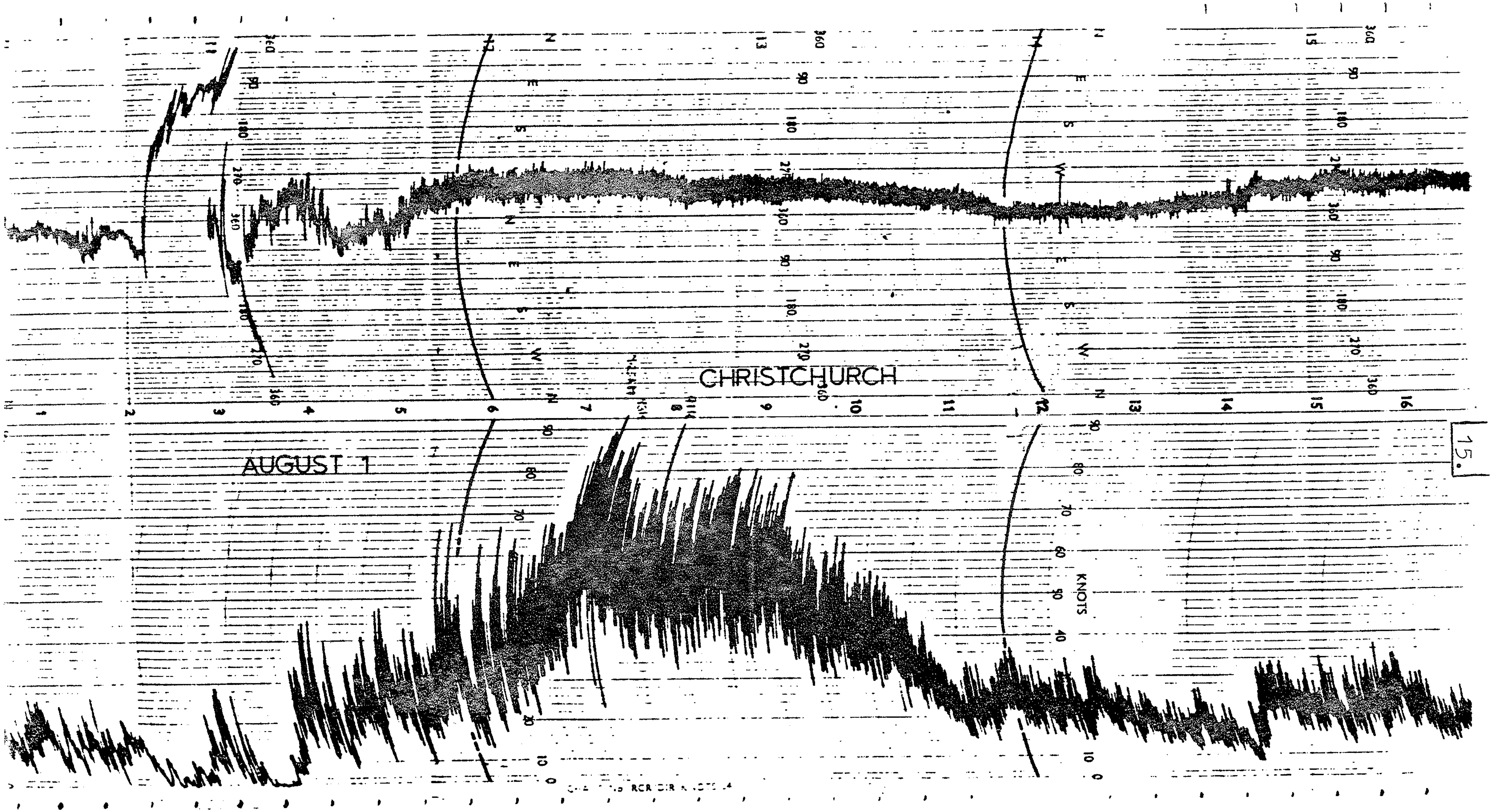

Fig. 4C. Anemometer charts, Christchurch Airport.
Speed scale in knots (1 m/s = 2 kt).

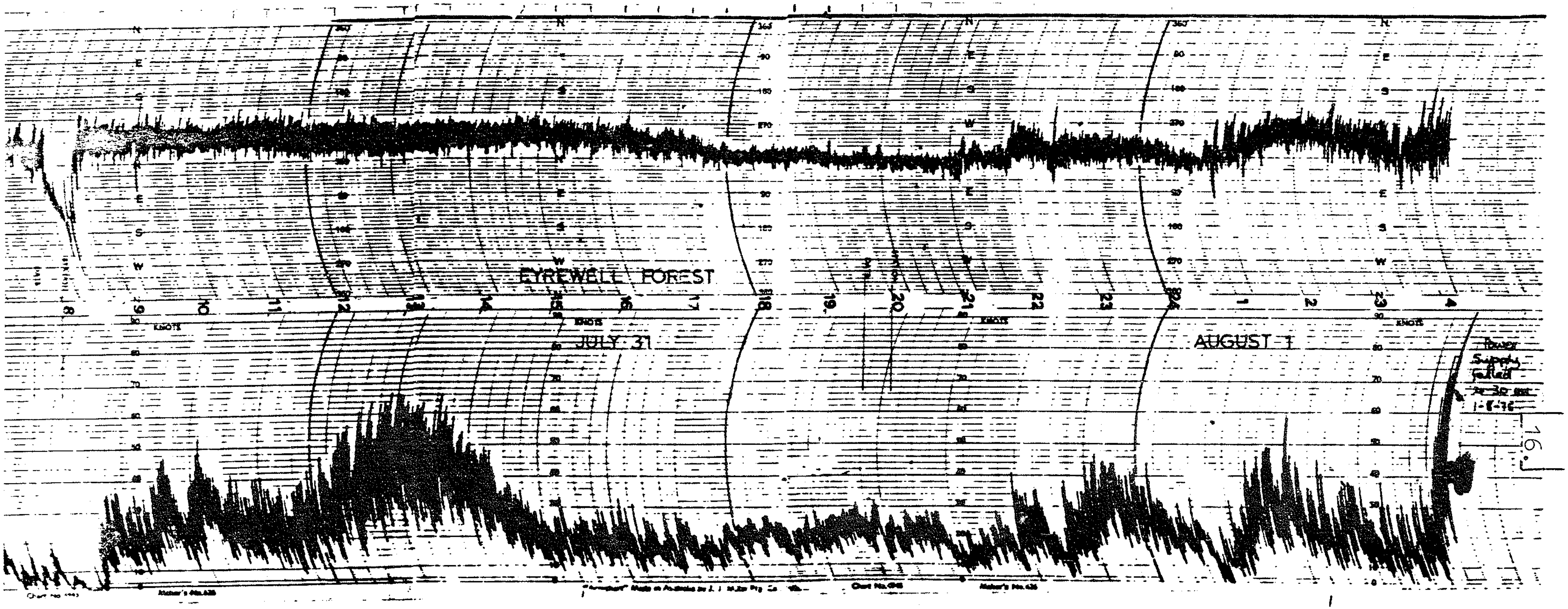

Fig. 4D. Anemometer charts, Eyrewell Forest
Speed scale in knots (1 m/s = 2 kt).

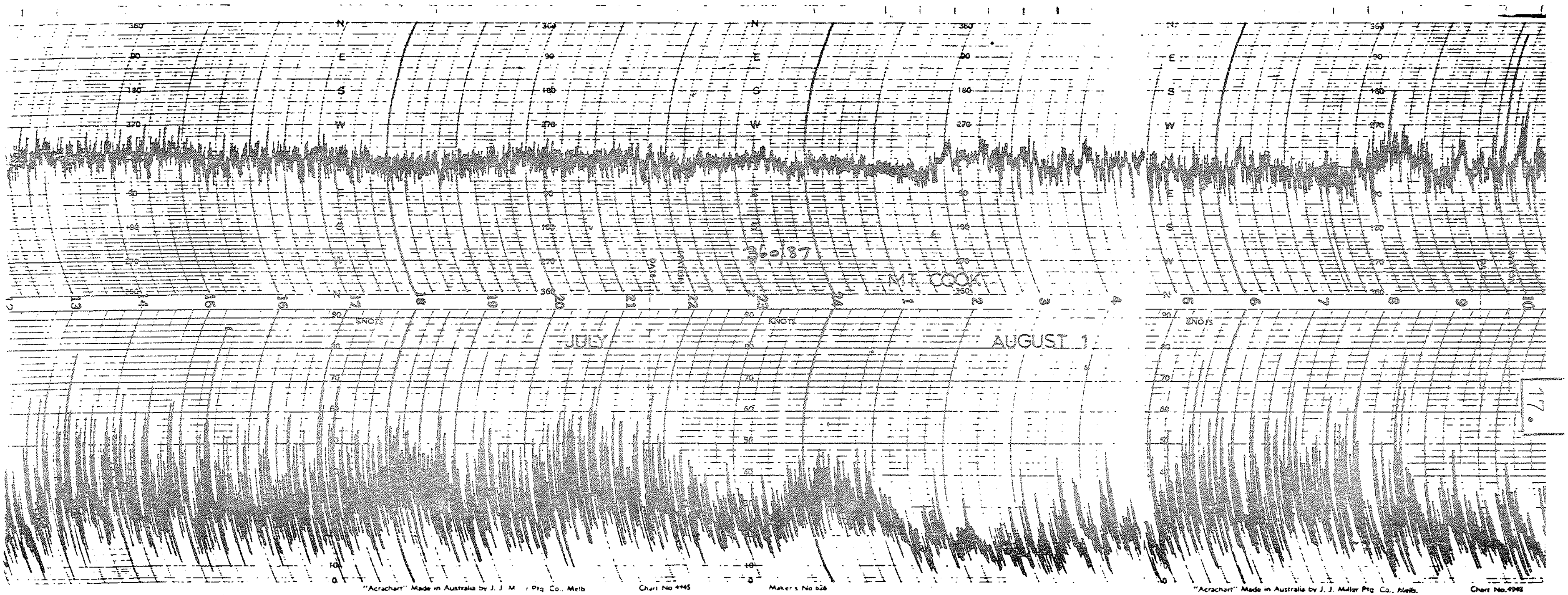

Fig. 4E. Anemometer charts, Mt Cook airstrip.
Speed scale in knots (1 m/s = 2 kt).

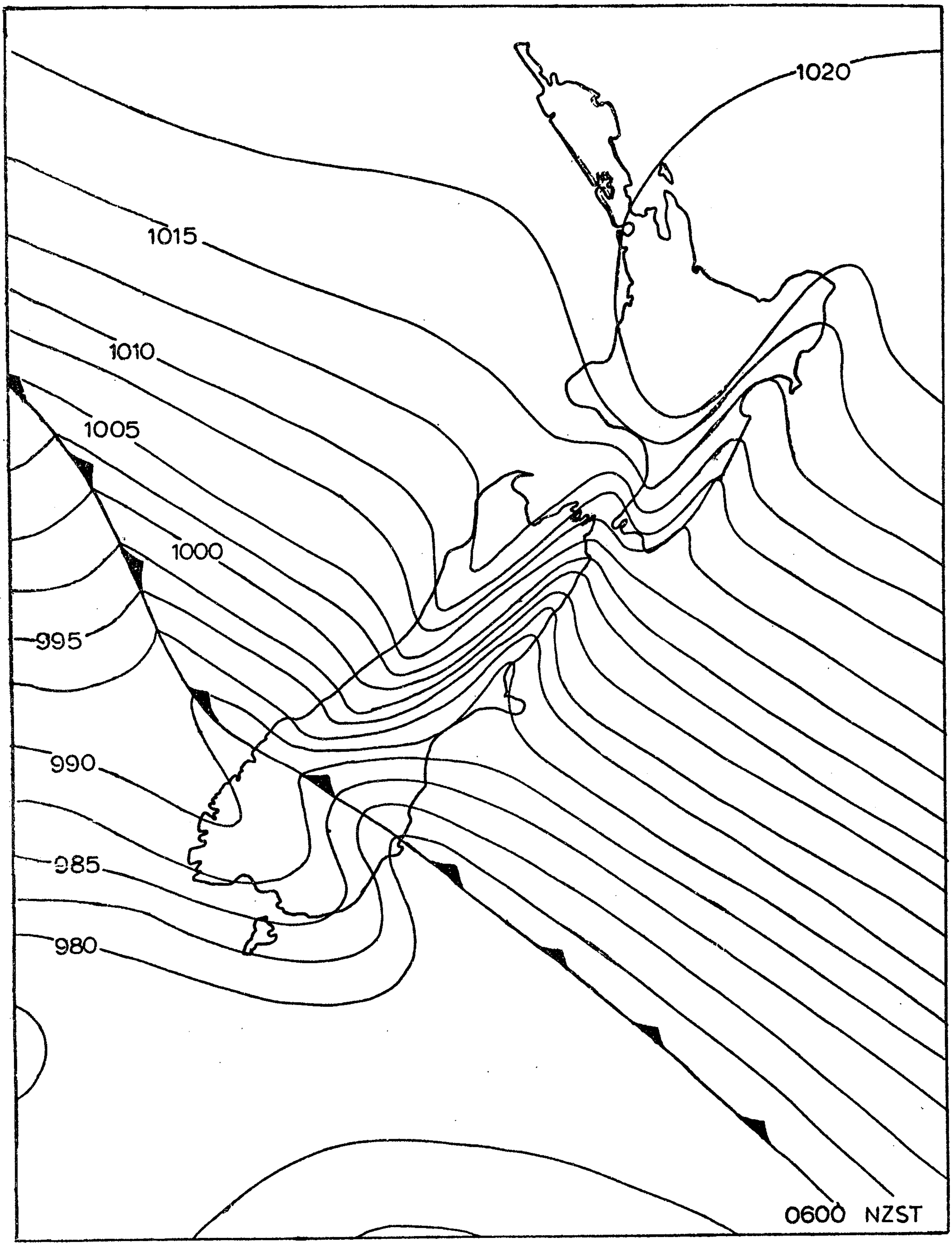

Fig. 5. Synoptic chart for 0600 NZST 1 August 1975.

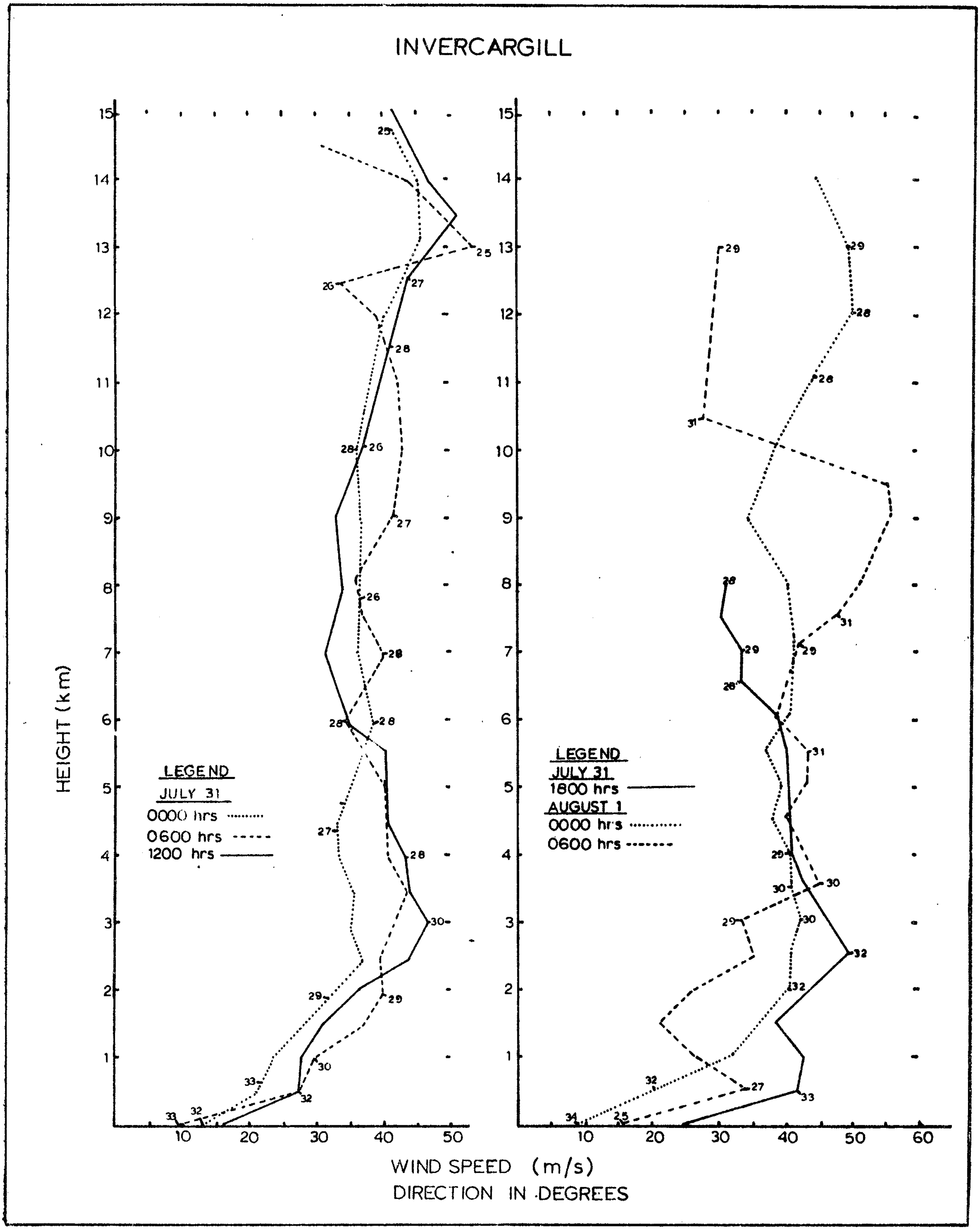

Fig. 6. Wind profiles for Invercargill.

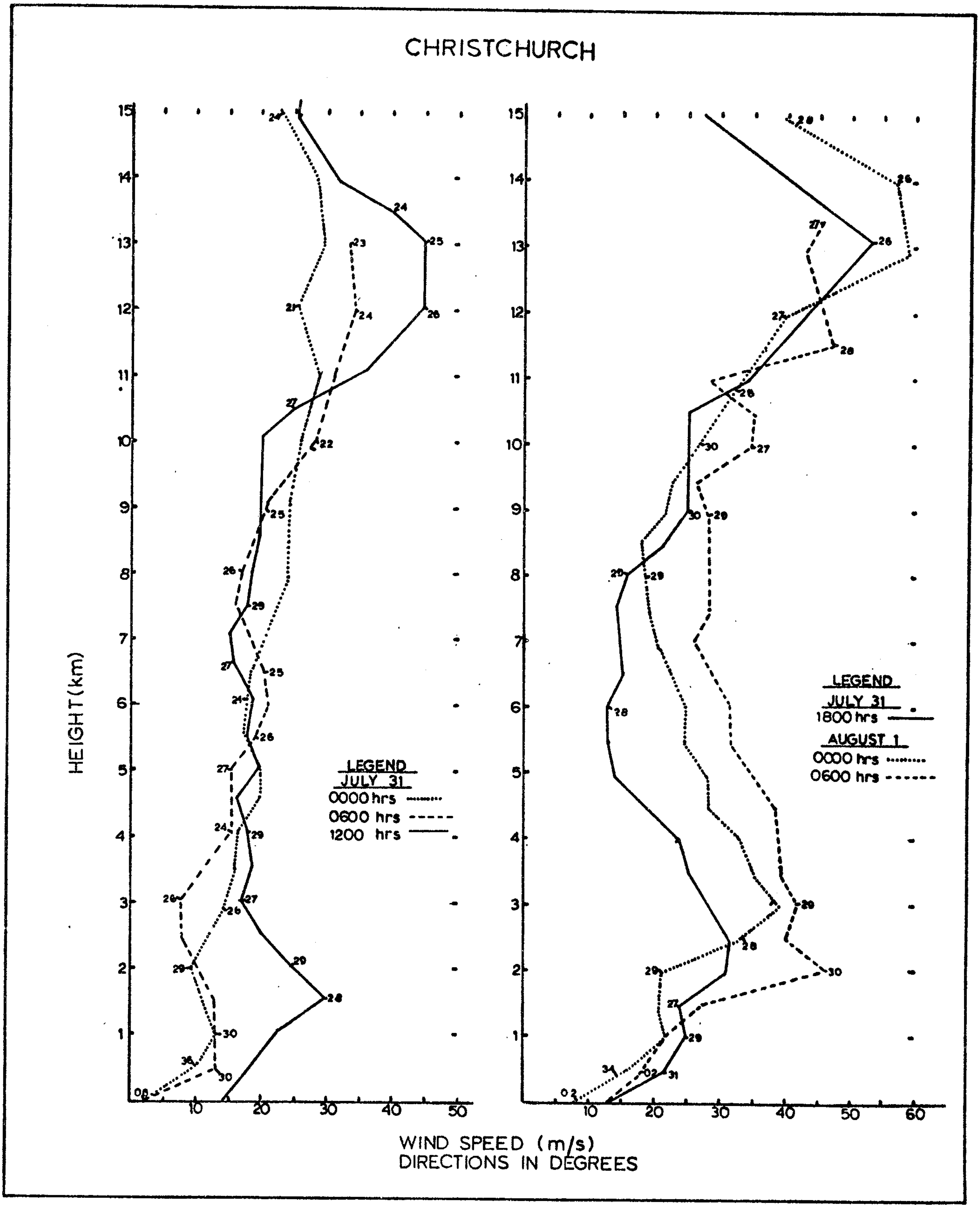

Fig. 7. Wind profiles for Christchurch.

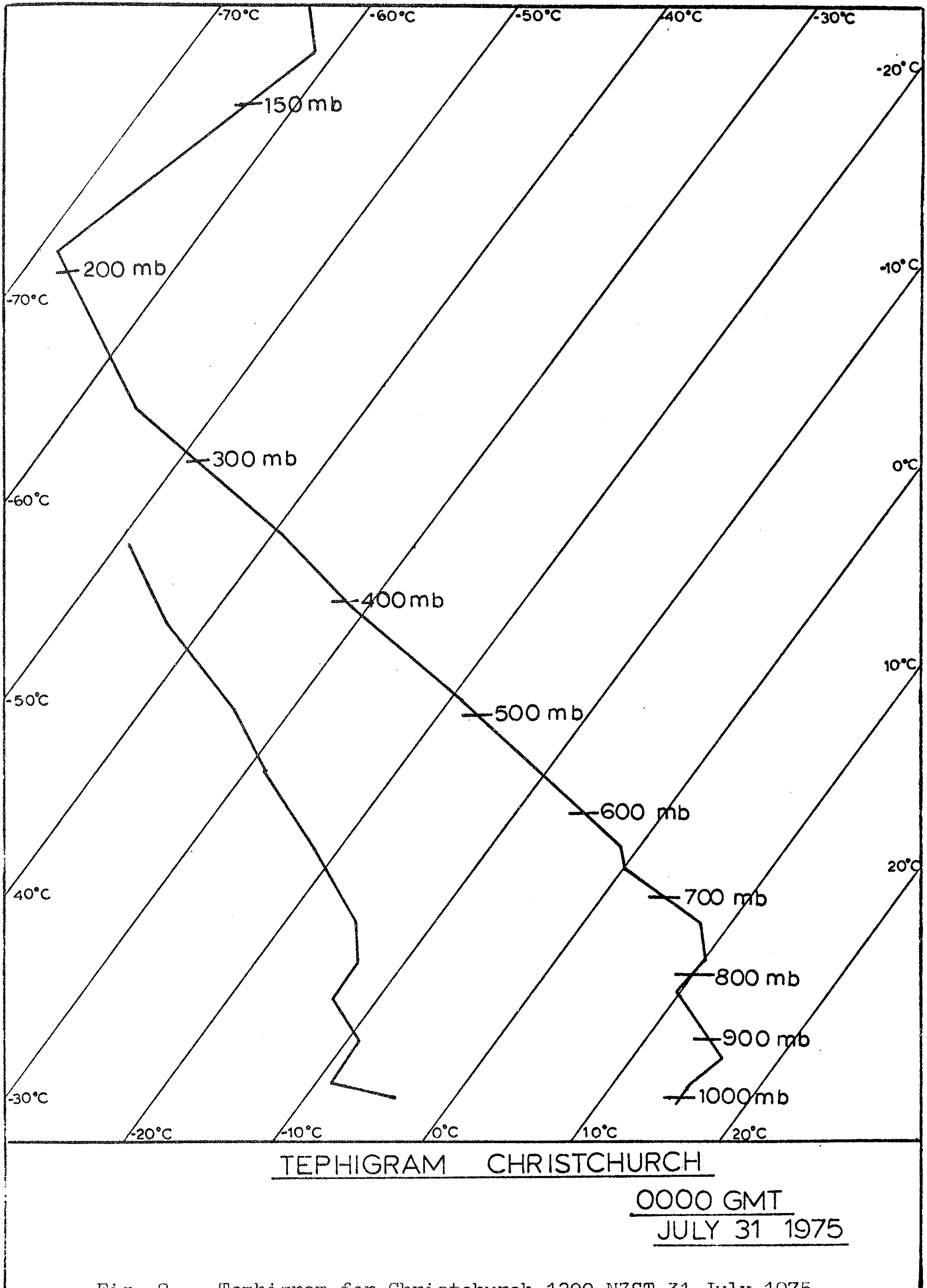

Fig. 8. Tephigram for Christchurch 1200 NZST 31 July 1975.

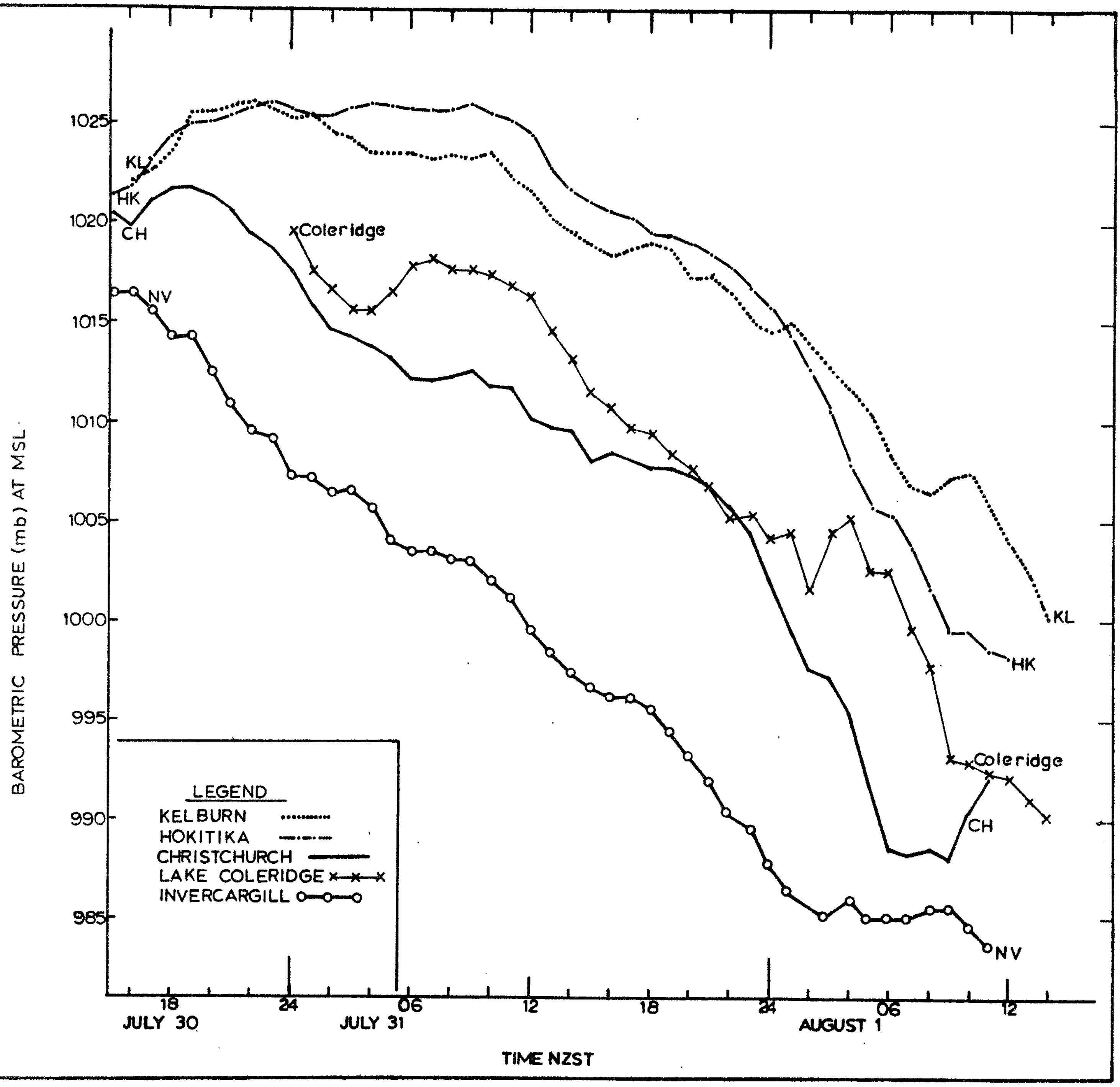

Fig. 9. Barograms for Kelburn (Wellington), Christchurch, Invercargill, Hokitika and Lake Coleridge.

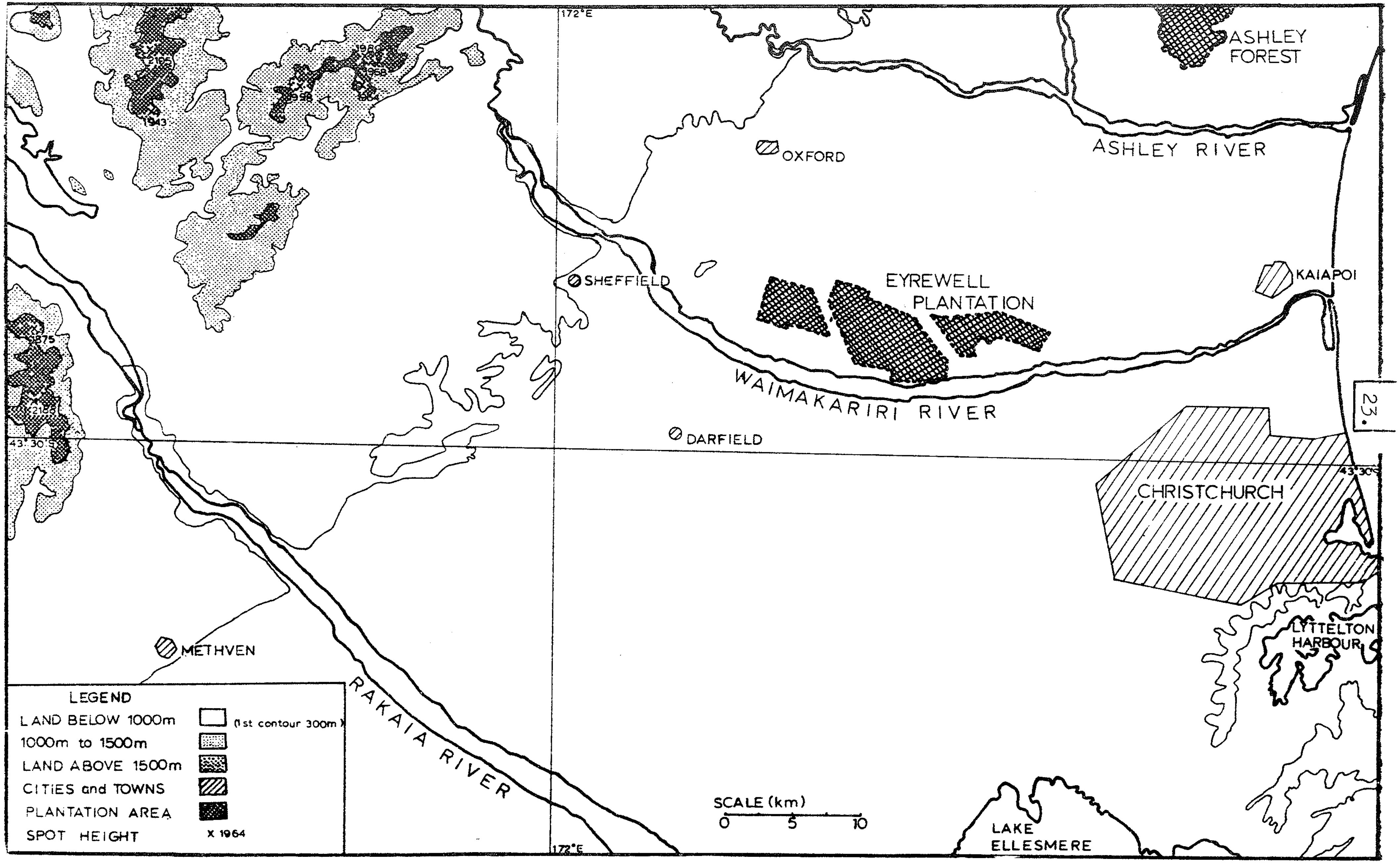

Fig. 10. Map of Eyrewell Forest and environs.