DEPARTMENT OF SCIENCE
AND THE ENVIRONMENT

BUREAU OF METEOROLOGY

TECHNICAL REPORT 25

SNOWFALL ON THE NEW SOUTH WALES SNOWY MOUNTAINS

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DECEMBER 1978

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Manuscript received June 1977
File 40/281

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SNOWFALL ON THE NEW SOUTH WALES SNOWY MOUNTAINS

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ABSTRACT

In this study, the synoptic situations which produce snowfalls on the Snowy Mountains are described. The topography of the area, because of its effect on the airstreams passing over it, is a major factor affecting the rate of snowfall on the mountains. Strong westerly airstreams in winter and early spring produce many heavy falls of snow. The synoptic situations associated with two periods of heavy snowfall in July and August 1974 are described. The annual variation in the maximum water content of the snowpack (W_{MAX}) is large. There was a biennial oscillation in annual W_{MAX} values over the period 1955 to 1968, with large W_{MAX} values occurring at four-yearly intervals. W_{MAX} values correlated significantly with mean values of a circulation index, L, calculated over periods ranging from three to five months. Significant lag correlations were found between W_{MAX} values at a snowcourse (elevation 2010 m) and the Hunter and Metropolitan East district average rainfall in January to June of the following year.

INTRODUCTION

The Snowy Mountains in NSW and the mountains to their north, the highest parts of the Great Dividing Range, are an important recreation area. The Kosciusko National Park includes much of the area. A major hydro-electric project, the Snowy Mountains Scheme, utilises the water resources.

Figure 1 is a topographical and location map of the area. Much of the terrain is above 1500 m. Mt Kosciusko (2226 m), the highest peak in Australia, is at the southern end of the Snowy Mountains. The headwaters of the Snowy River are located just below the summit of this mountain. The western slopes of the Snowy Mountains are precipitous, but on the eastern side they slope more gently to the Snowy River Valley. To the east of this river rises the Ramshead Range, the eastern side of which slopes steeply to the Crackenback River.

Thredbo Village, Perisher Valley and The Smiggin Holes are the main centres for downhill skiing. The latter two skiing areas are on the eastern slopes of a short range about 8 km to the east of the Snowy Mountains.

Generally, the effect of the terrain on precipitation is to produce an increase with elevation. Paulhus (1973) says 'Concomitant with increased precipitation on windward slopes is the decrease on lee areas. Immediately to the lee of ridges, however, is a spillover zone where precipitation produced by the forced ascent of moist air over windward slopes can be as great as on the ridge. Because of the relatively slow fall velocity of snowflakes, spillover extends much farther beyond the ridge for snow than it does for rainfall'.

Gaffney (1971) estimated the median rainfall over the Snowy Mountains area. He concluded that the small areas on the western slopes above 1800 m would have median annual rainfall of about 3800 mm. The only areas in Australia that have higher rainfall are the north Queensland coast near Innisfail, which has a median annual rainfall of about 4300 mm, and parts of the west coast of Tasmania.

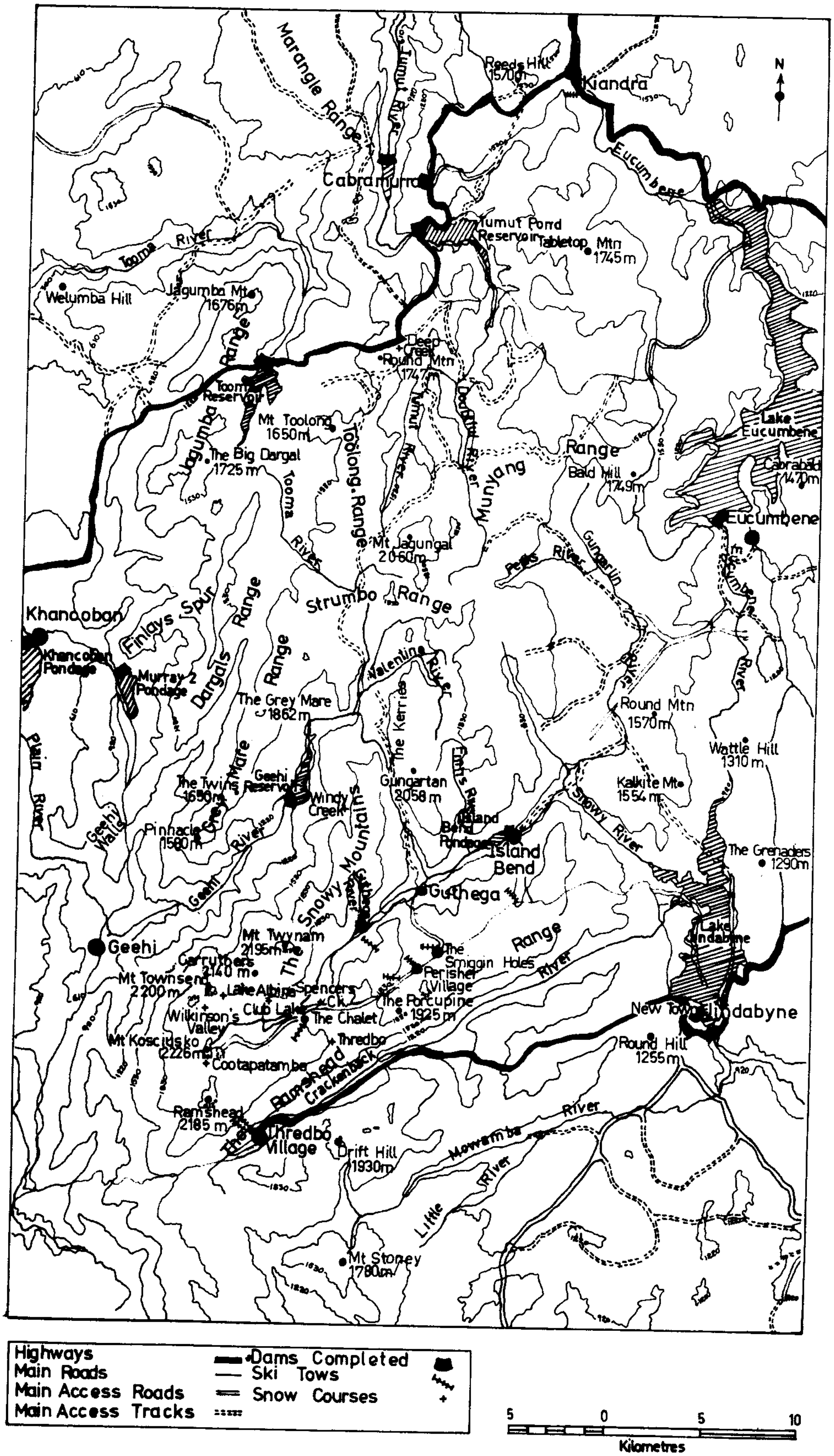

Fig 1 Topographical and location map

This study is concerned with snowfall over the area. Snow can fall at any time of the year on the highest parts. Gaffney (1971) says 'In winter (June-August), above 4000 ft (1200 m), snow represents about 70 per cent of the total precipitation; for the year as a whole about 30 per cent of the total precipitation is in the form of snow above this level'.

Walsh (1961) presents graphs of the percentage of precipitation days on which measurable snow occurred at Island Bend, Cabramurra and Spencers Creek. These are reproduced in Fig 2. The October value for Cabramurra seems too low. Although there is only a small difference in elevation between Cabramurra and Island Bend, the percentage of precipitation days on which measurable snow occurred differs greatly. While some of the difference is due to the elevation factor, much occurs because the two townships are located on opposite sides of the ridge, Cabramurra on the western and Island Bend on the eastern side. In a westerly stream, which produces much of the winter precipitation in the area, air ascending on the western slopes will cool at the dry adiabatic lapse rate until saturated or at a greater rate due to evaporative cooling if rain is falling, then at the saturated adiabatic lapse rate. After reaching maximum elevation, the parcel will descend and warm at the saturated adiabatic lapse rate until the relative humidity is less than 100 per cent, and then warm at the dry adiabatic lapse rate, or less than this if precipitation is present. However this effect, as will be seen later, may be modified at certain elevations and distances from the ridge line, when spillover of precipitation particles occurs.

SNOW-PRODUCING SYNOPTIC SITUATIONS

Cold pools

Bahr and Armstrong (1971) describe a situation where an upper level cold pool produced heavy snowfalls. The greatest snowfall rates are probably associated with situations of this type because snowflake production is favoured by cloud systems with moderate and steady updrafts, the relatively light windspeeds at low levels result in an even snow cover, the low temperatures produce snowfalls to low elevations and the snowflakes maintain their shape when they fall, producing, on the ground, a deep cover of lightly packed snow known as powder snow. In these situations the snow producing mechanism is the vertical motion produced by the upper level low. The effect of topography is probably of secondary importance. This type of synoptic situation occurs infrequently and usually exists over the Snowy Mountains area for a short period.

Cold prefrontal northwesterlies

Another synoptic situation which produces heavy snowfalls for a short period is a rather cold northwest to west-northwesterly stream ahead of a cold front. Pitt (1971) states 'Experience has shown that the most likely wind for snow formation is the cold westerly which includes southwest and northwest components. Examination of intensity of snowfall produced when these wind directions prevail in turn indicates that the heaviest falls most often occur when a cold northwesterly predominates and not, as might be expected, when the colder southwesterly affects the region... The northwesterly proves more favourable because of the amount of water vapour it contains'.

The snow producing mechanisms in this situation are vertical motion produced by:

(a) the front when it is close to the mountains, and

(b) forced ascent of the air over the mountains.

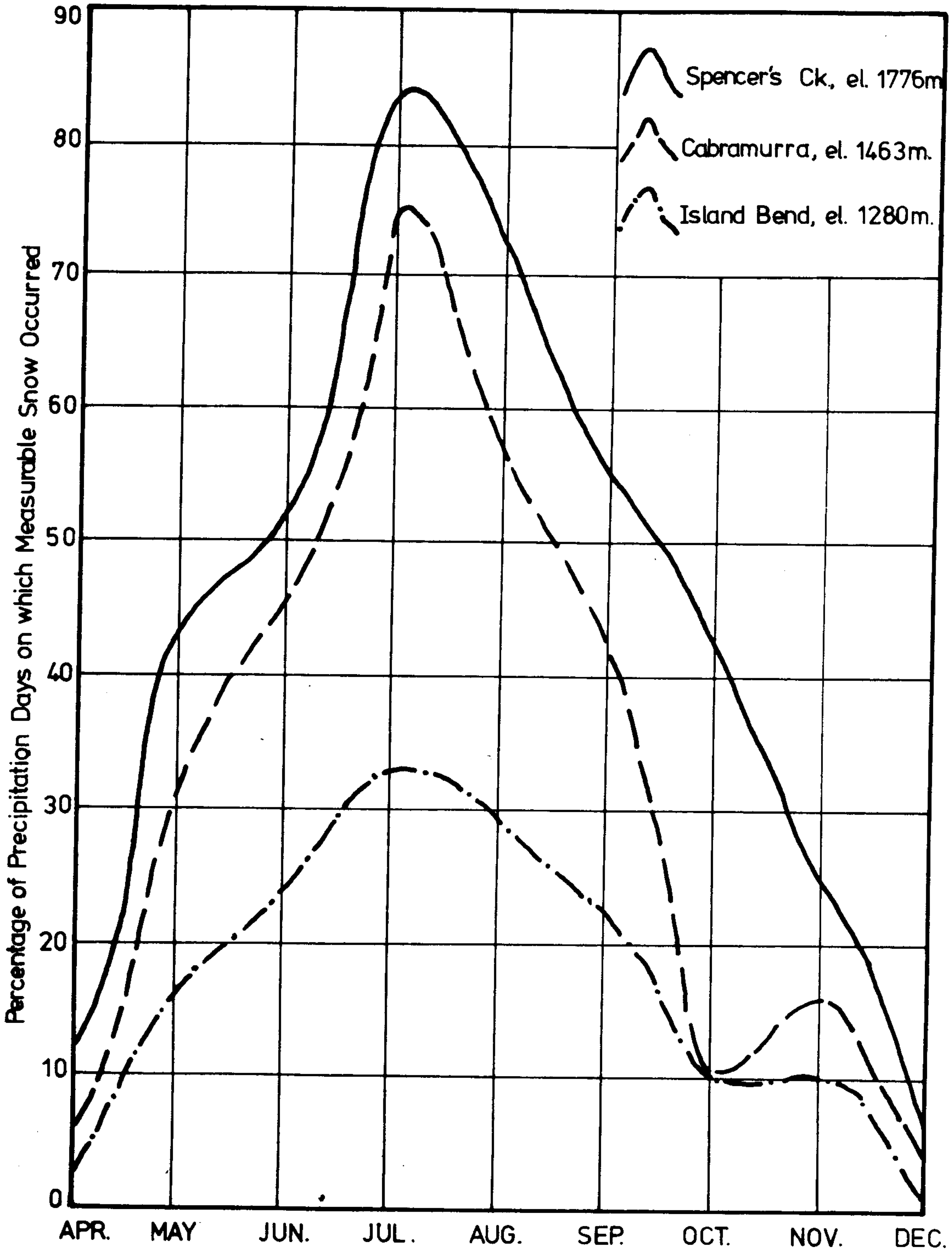

Fig 2 Percentage of precipitation days on which measurable snow occurred (1954-1960)

Strong westerlies

The situation that produces many of the major snowfalls over the higher parts of the Snowy Mountains (above about 1500 m) is a strong and persistent westerly stream. In winter and spring, 'blizzard' conditions often persist for several days above this level with this type of airflow. A case study of a strong, persistent westerly stream is given later. With such an airstream the snow (often graupel or snowpellets) producing mechanism is vertical motion produced by forced ascent of air over the mountain barrier.

Usually the depth of moisture on the windward side of the mountain is shallow (often only 2000 to 3000 m deep) and the freezing level high. The effect of uplift over the mountains is to produce:

(a) a cloudbase below the level of the top of the mountains and cloud tops which may extend 6000-8000 m above them;

(b) a lower freezing level over the mountains than in the free air on the windward side;

(c) very strong windspeeds over the higher parts of the mountains.

A quick method of estimating the freezing level over the mountains in a strong westerly airstream is to:

(a) estimate the surface temperature and dew-point of the airstream upwind of the mountains (night or early morning temperature observations should not be used unless one is sure that an inversion is not present. Air beneath an inversion is decoupled from the gradient flow);

(b) raise this parcel adiabatically on a log p-skew T diagram to 1900 m (most of the ridgeline of the Snowy Mountains is above this level).

If the temperature of this parcel is 0°C before the 1900 m level is reached then the elevation at which this occurs is the estimated freezing level. If the freezing level is not reached by 1900 m then the low level temperature and dew-point profile on the windward side of the mountains will have to be estimated and representative levels on this profile lifted adiabatically by 1900 m.

Usually this method will overestimate the height of the freezing level because, in a strong westerly flow, severe mechanically induced turbulence occurs and the air at low levels is well-mixed. Mixing and lifting usually produces a lower freezing level than adiabatic lifting. If the windspeed at low levels is not strong enough, the air near the surface will not be lifted over the ranges. Thirty knots is a subjective estimate of the windspeed at 1000 m, on the windward side of the mountains, required to cause low level air to be lifted over the ridge of the Snowy Mountains.

While the moisture content of this type of airstream is not high, snowfall rates can be quite substantial because the strong low level wind speeds, normal to the mountain range, produce high vertical velocities as the air ascends over the barrier, resulting in large vertical fluxes of water vapour. When this airstream persists for several days, snow falls continuously and produces a deep cover on the higher parts of the mountains.

Paulhus (1973) describes models from which orographic precipitation amounts and trajectories can be calculated. Mason (1971) presents a graph showing the terminal velocities of snow crystals as a function of their linear dimensions. The linear dimension is defined as the diameter of the sphere which will just contain the crystal. The terminal velocity of graupel, known in the Snowy Mountains area

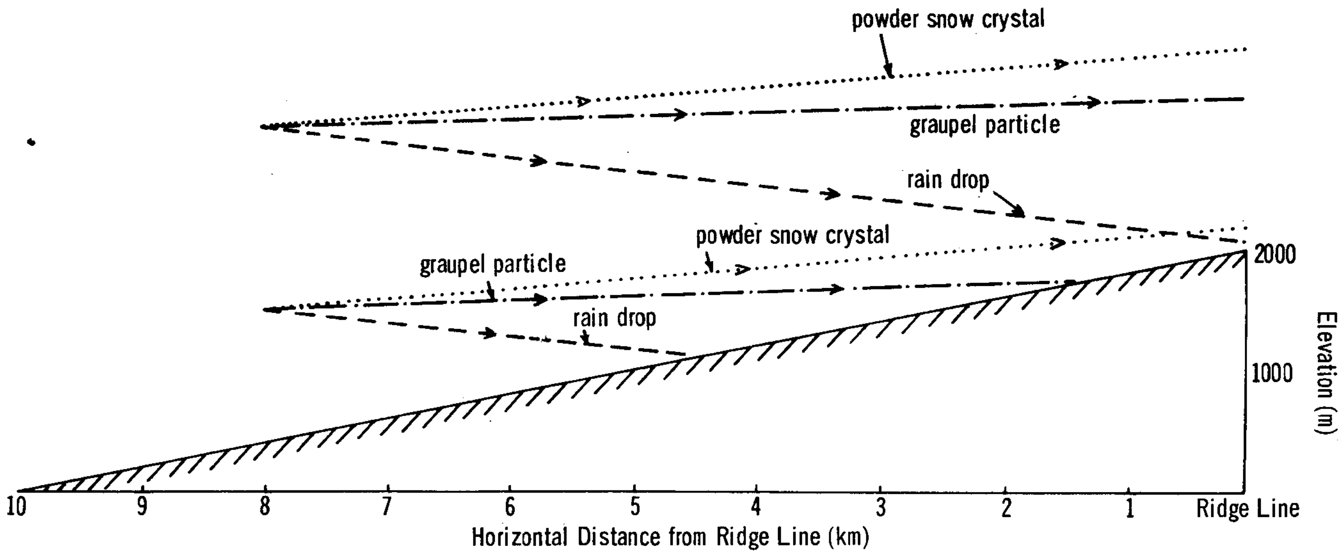

Fig 3 Trajectories of various precipitation particles formed by orographic lifting

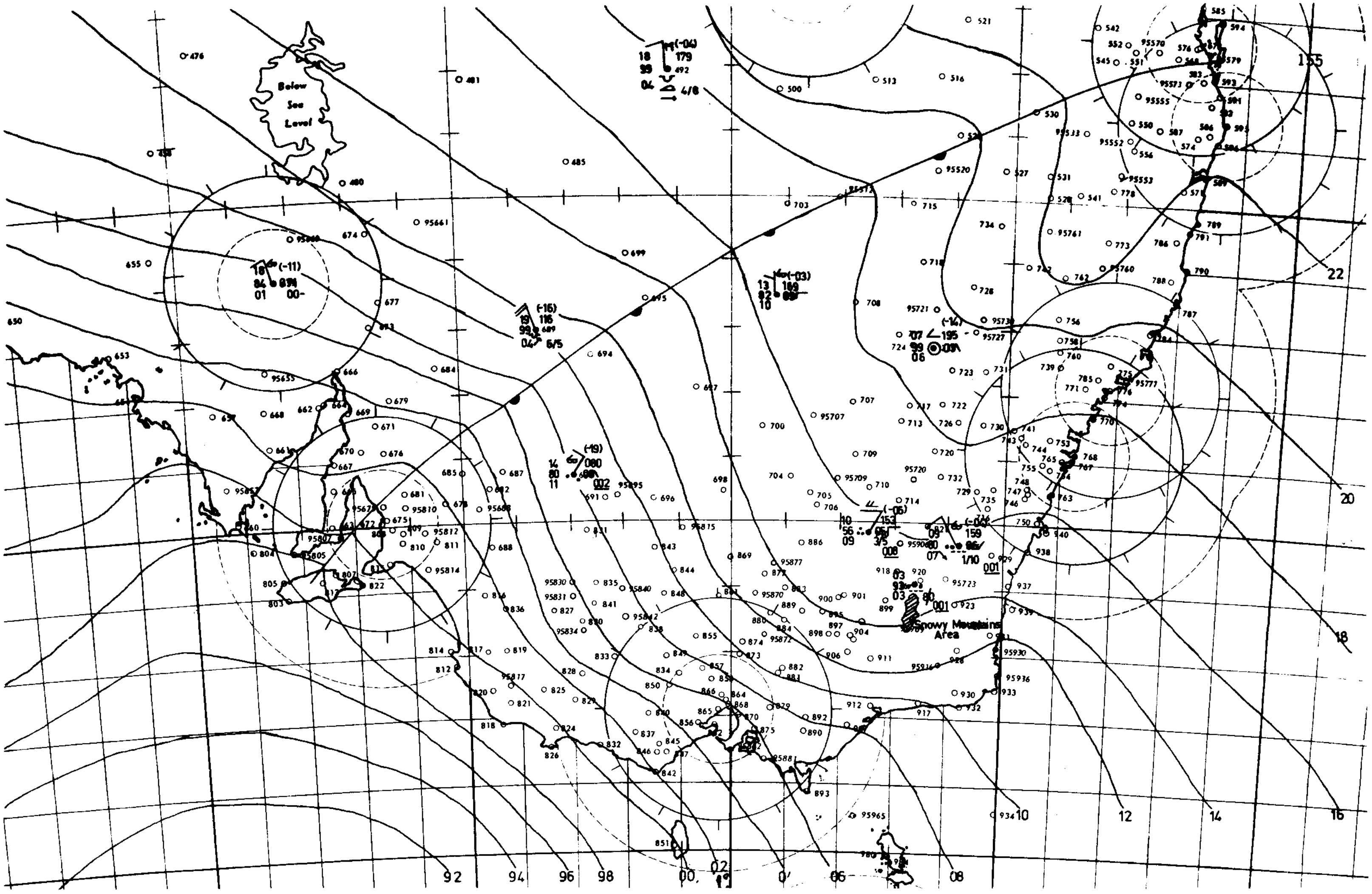

Fig 4(a) MSL synoptic chart 0900 EST 17 July 1974

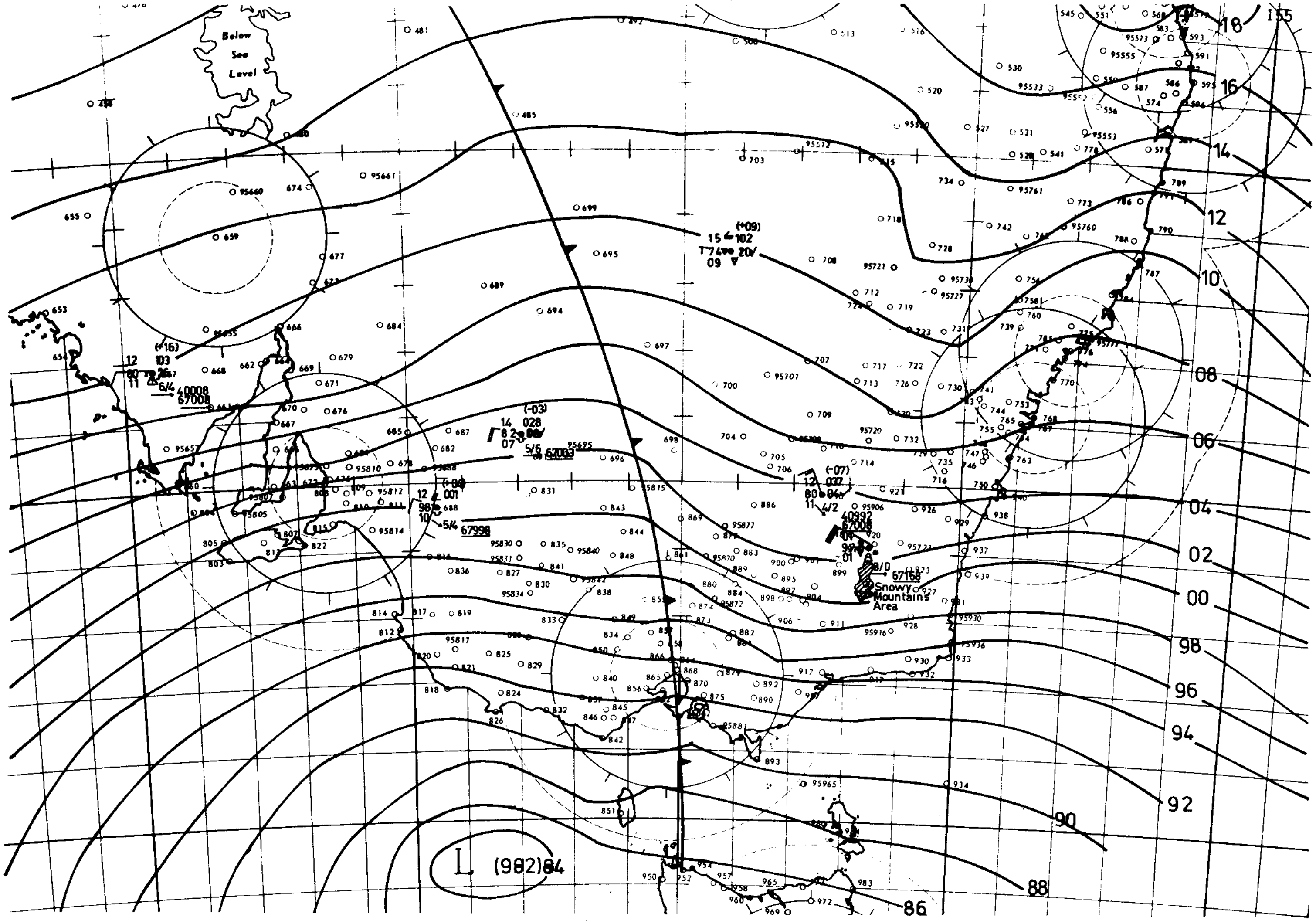

Fig 4(b) MSL synoptic chart 0900 18 July 1974

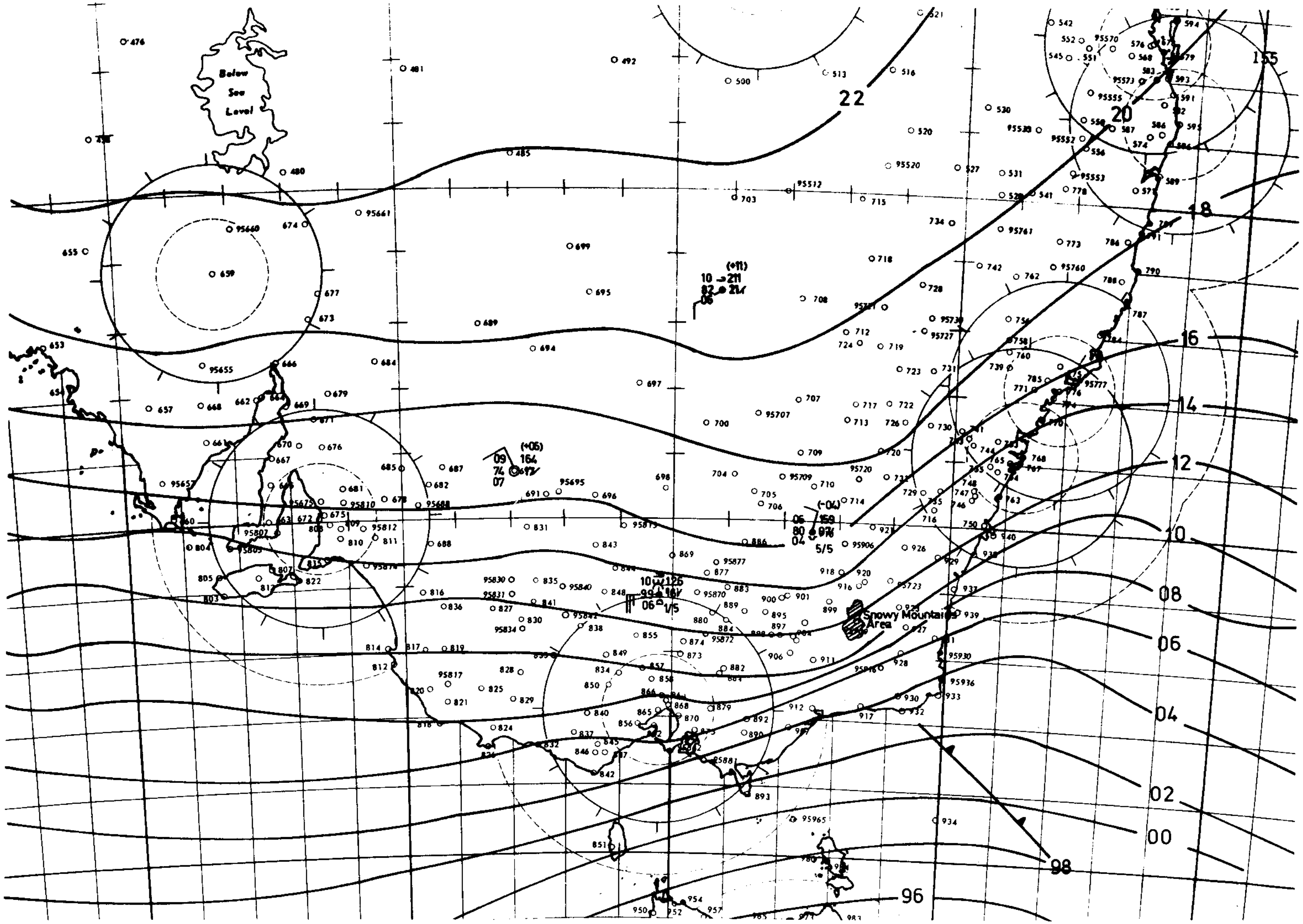

Fig 4(c) MSL synoptic chart 0900 EST 21 July 1974

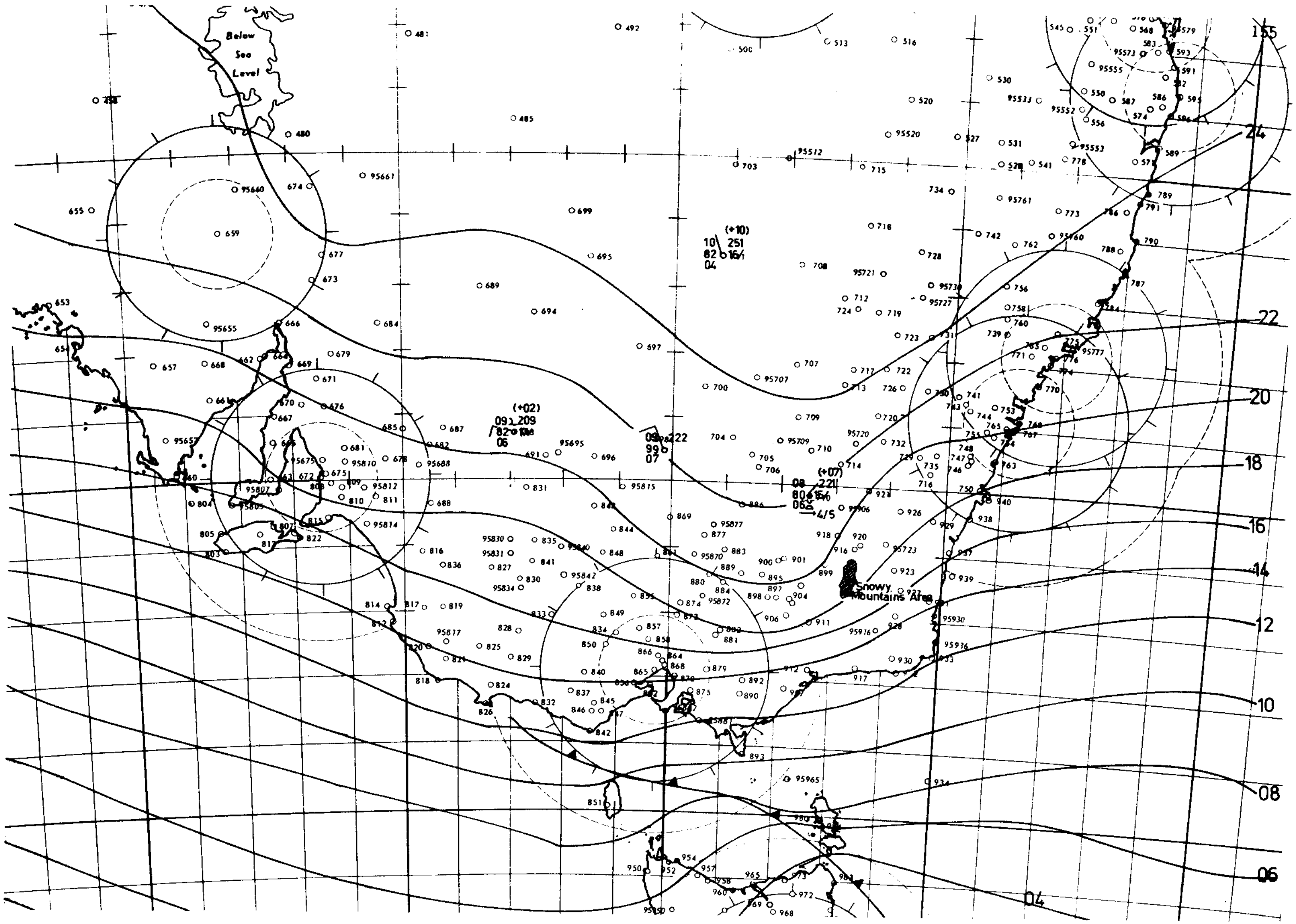

Fig 4(d) MSL synoptic chart 0900 EST 22 July 1974

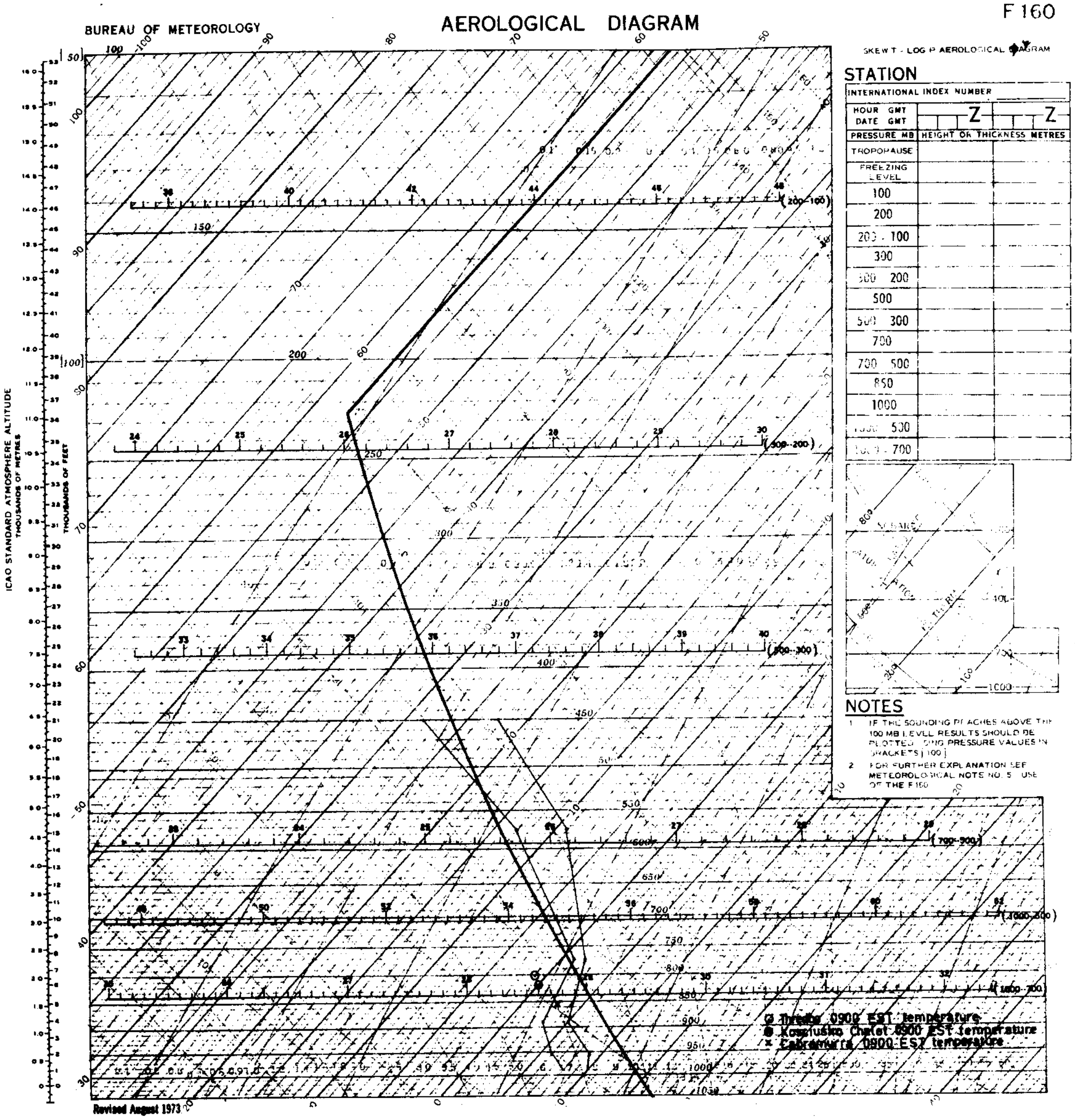

Fig 5(a) Environmental temperature and dew-point sounding at Wagga 0900 EST 17 July 1974 as sago snow, ranges from about 1.2 m/s for a crystal of dimension 1.7 mm to 2.7 m/s for a crystal of dimension 5.5 mm. The terminal velocity of powder snow, 0.5 m/s, is independent of crystal dimension. A very simple model is given in Fig 3 which shows how the type of precipitation affects its distribution. A simplified cross-section of the topography along a latitude line is shown. An air parcel is assumed to move directly up and parallel to the slope with a velocity of 15 m/s. Hence the air would have a vertical velocity of 2.9 m/s. In practice, convergence of the airstream as it ascends the slope causes windspeeds near the ridgeline to be higher than those upwind. The trajectories of powder snow crystals, 2 mm diameter graupel particles (terminal velocities 2 m/s) and 2 mm diameter raindrops (terminal velocities 6.5 m/s) are shown from points 1500 m and 3000 m elevation and 8 km upstream from the ridge line. Both powder snow trajectories clear the ridgeline. The raindrop trajectory from the higher point just clears the ridge, while the graupel particle trajectory from the lower point hits the slope at an elevation of about 1750 m, 1.4 km upwind of the ridge.

Although Fig 3 grossly oversimplifies the situation, it can be readily seen that much of the snow and graupel which is formed on the windward slopes of the range will be precipitated, or melted and evaporated on the lee side.

Cold southerly airstreams

Shanahan (1967) describes three cold outbreak situations in 1966 that produced snow on the Central and Southern Tablelands of NSW. Although cold southerly or southwesterly airstreams produce snowfalls to very low levels on the Southern Tablelands, falls on the higher parts are usually not heavy. There are several reasons for this:

(a) the precipitable water in these airstreams is usually very low;

(b) in a strong westerly stream, the airflow is normal to the main ridgeline and most of the air ascends over the barrier but, in a southerly stream, the flow is almost parallel to the main ridgeline so much of the air can diverge around the barrier;

(c) a deep southerly stream rarely lasts for more than two days;

(d) if the stream is from the southwest, the air passes over the Victorian Highlands before reaching the Snowy Mountains area. Hence much of the moisture in the airstream is precipitated before the air reaches NSW.

Reported 24 hour snowfalls soon after the start of a cold outbreak are often large. However much of the snow falls in the prefrontal west or northwesterly stream.

TWO CASE STUDIES

17 to 23 July 1974

Figs 4(a) to (d) are the 0900 EST MSL charts of 17, 18, 21 and 22 July 1974 respectively. Fig 4(a) shows a mild and very moist north-northwesterly airstream ahead of a warm front. Dew-points ahead of the front were 10°C and 11°C. Snow was falling at Kosciusko Chalet (1769 m), but by 0900 EST the next day 168 mm of rain had fallen. Table 1 gives the 0900 observations at Kosciusko Chalet from 17 to 23 July and Table 2 the 0900 EST observations over the same period at Cabramurra (1463 m), Kiandra (1395 m) and Thredbo (1957 m). Most of the precipitation on 17 and 18 July was rain and much of the 168 mm at Kosciusko Chalet would have fallen ahead of the warm front evident on the 0900 EST surface chart on 17 July (Fig 4(a)). At this time, the top of the warm front at Wagga was 780 mb (see Fig 5(a)). The frontal slope was 1 in 190. Temperatures at Thredbo, Kosciusko Chalet and Cabramurra are plotted in Fig 5(a). Those at Thredbo and Kosciusko Chalet indicate that the air below 900 mb was lifted adiabatically over the mountains. The McGrath

Snow Index (MSI), which was developed in the NSW Regional Office, indicated that snow would not fall. Details of this index are given in the Appendix.

By 0900 EST on 18 July, the temperature had fallen to 0.5°C at the Chalet and hail showers were reported. The maximum temperature for the previous 24 hours was 5°C. The MSL chart (Fig 4(b)) shows a strong westerly stream over the area with a weak cold front in the westerlies approaching. Wet snow began to fall at the Chalet by the evening of 18 July and dry snow fell during the night. The 0900 temperatures at the four mountain stations shown in Fig 5(b) suggest that the air below about 840 mb was being completely mixed resulting in a mixing condensation level of about 840 mb (1600 m). Thredbo (1957 m) and Kosciusko Chalet (1769 m) were both in cloud, but the cloudbase was above the level of Cabramurra (1463 m) and Kiandra (1395 m). This verifies that the cloud base was at about 1600 m.

By 0900 EST on 19 July a strong west-southwesterly airstream had become established, the temperature had fallen to -1.8°C at the Chalet and 37.5 cm of new snow had accumulated on the ground during the previous 24 hours. The snow that fell into the gauge, a Nipher snowgauge, measured 118 mm when melted. Thirty centimetres of new snow is usually taken as having a water equivalent of about 25 mm of rainfall. On this basis 118 mm of rain is equivalent to 142 cm of snow, more than three times the depth observed. One, or a combination of the following factors could explain this disparity:

(a) blowing snow could have accumulated in the gauge;

(b) the snow could have been packed by wind action as it fell;

(c) initially the snow was wet and much of it may have melted;

(d) snow may have been blown from the measuring point.

Comparison of Figs 5(b) and 5(c) shows that temperatures below 500 mb, to the west of the ranges, had fallen by 4° to 5°C in the 24 hours to 0900 EST on 19 July. The MSI on 19 July indicated light to moderate snowfalls above about 1200 m.

Over the next few days the strong westerly stream was maintained. Snow was reported at the Chalet at every 0900 observation from 19 to 22 July inclusive. At 0900 on 22 July (Fig 4(d)) the westerly gradient had slackened and by 23 July snow had stopped falling at all of the mountain stations.

Fig 5(d) shows the environmental temperatures and dew-points at Wagga at 0900 on 21 July 1974. There was very little moisture above 775 mb. The MSI indicated light to moderate snowfalls above 1200 m.

Windspeeds at 1000 m to the west of the Snowy Mountains from 19 to 22 July inclusive were from 30 to 40 knots. On 23 July, when the snow had stopped, the 1000 m windspeed had dropped to 25 knots and the temperatures at the mountain observation stations were about the same as temperatures at the same level in the free air to the west (see Fig 5(e)). The low level air was much drier than over the previous few days.

In Figs 5(b) to (d), the method of estimating the freezing level on the mountain slopes, previously described, is demonstrated. A surface temperature and dew-point representative of the air upstream of the mountains has been lifted adiabatically. Excepting in Fig 5(b) the temperatures at the mountain stations are within 1°C of those estimated from the lifted parcel. The surface air shown in Fig 5(e) was not lifted over the mountains, because the air beneath the inversion was decoupled from the air above.

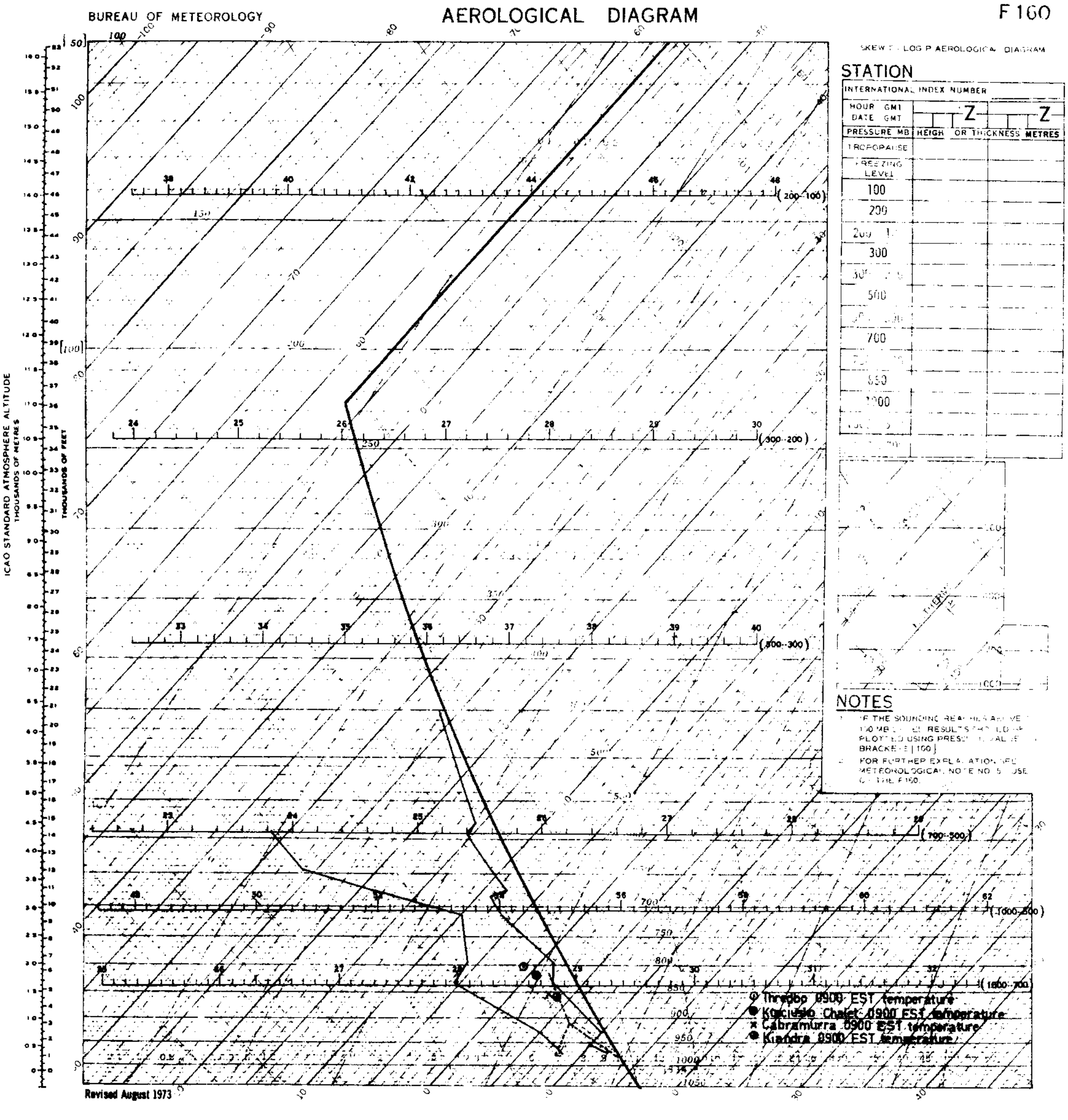

Fig 5(b) Environmental temperature and dew-point sounding at Wagga 0900 EST 18 July 1974

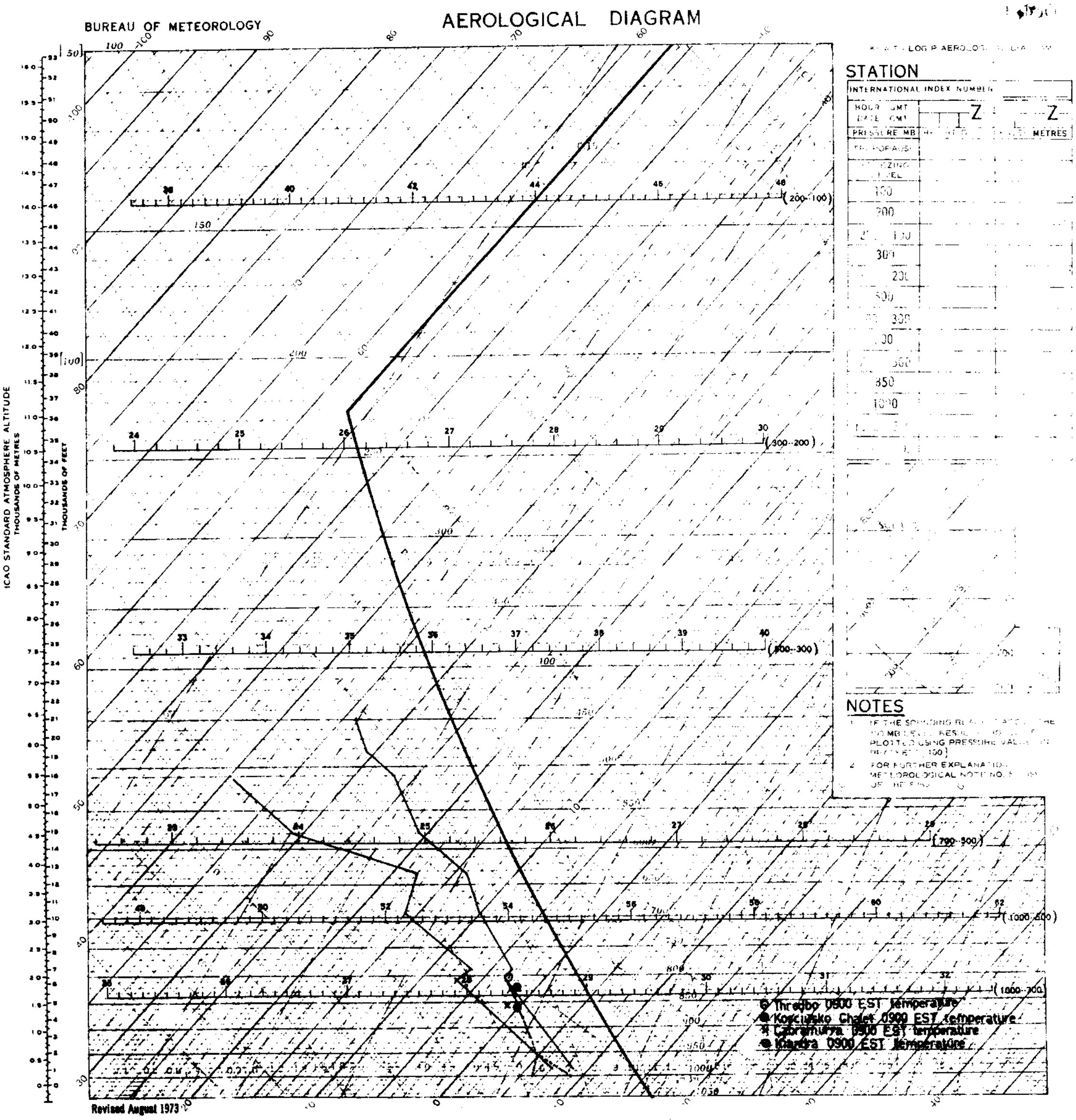

Fig 5(c) Environmental temperature and dew-point sounding at Wagga 0900 EST 19 July 1974

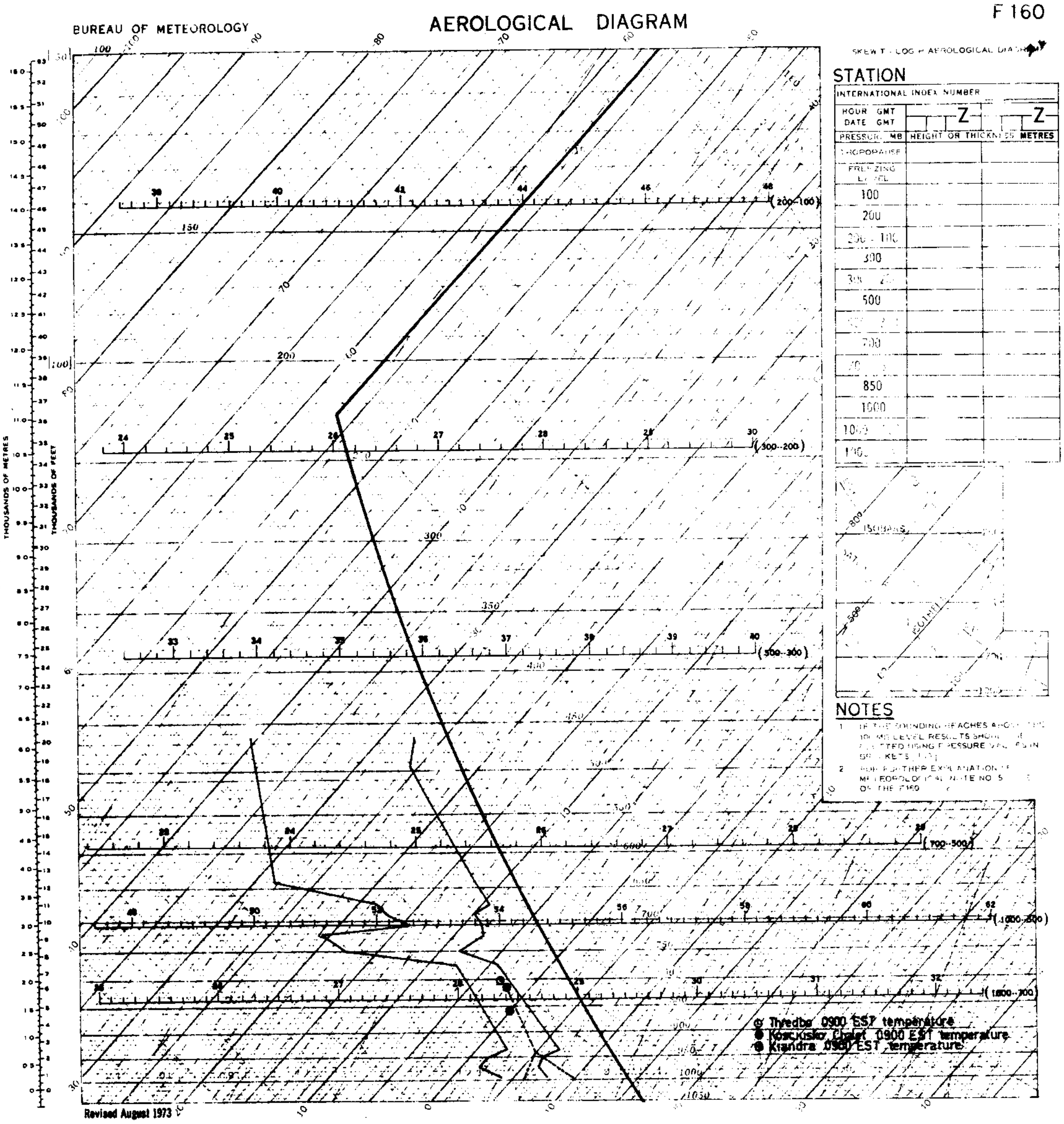

Fig 5(d) Environmental temperature and dew-point sounding at Wagga 0900 EST 21 July 1974

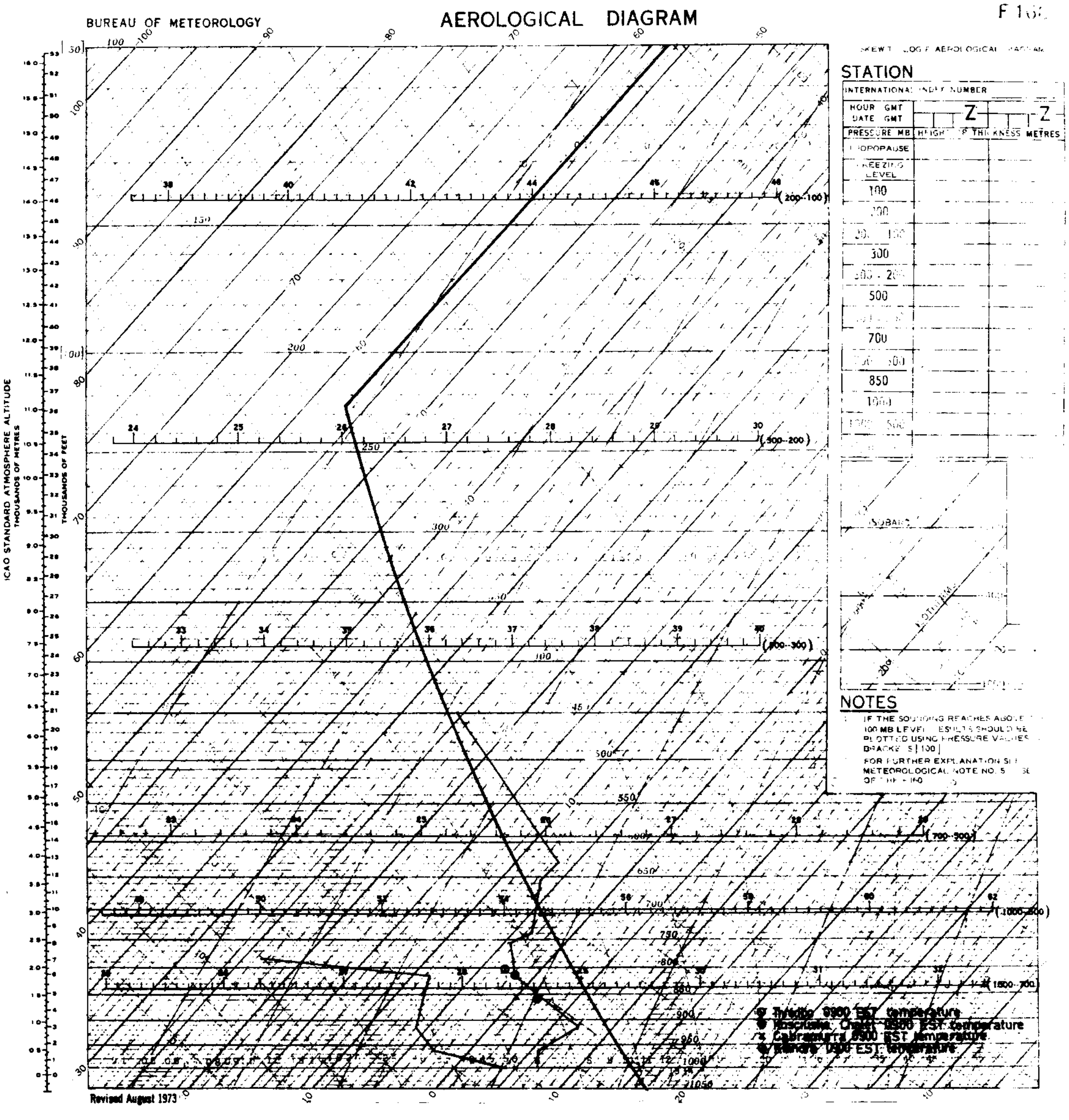

Fig 5(e) Environmental temperature and dew-point sounding at Wagga 0900 EST 23 July 1974

Table 1 0900 observations at Kosciusko Chalet (1769 m) from 17 to 23 July 1974

Date	DB (°C)	WB (°C)	DP (°C)	Wind (kt)	VIS	Cloud amount type & height (hundreds of metres)	Present weather	Past weather	24-hour rainfall (mm)	Max (°C)	Min (°C)	Gale?	Comments	Snow depth (cm)
17	0.1	0.1	0	NE 26	500 m	8 Cu 00 from W	Snow & hail mod.	Snow & hail	15.8	1.5	-3.4	Yes	Rain, hail, sleet & sago	
18	0.5	0.5	-1	NW 30	500 m	8 Cu 00 from W	Showers of slight hail	Rain cont. heavy	168.0	5.0	-0.5	Yes	Rain & hail	
19	-1.8	-1.8	-2	N 28	500 m	8 Cu 00 from W	Heavy cont. snow	Mod cont. snow	118.0	1.6	-2.4	Yes	Wet snow changing overnight to dry snow	37.5 new
20	-1.7	-1.7	-2	SSW 30	500 m	8 CU 00 from S	Heavy cont. snow	Heavy snow	42.0	-1.5	-3.2	Yes	Snow, sago	
21	-1.8	-2.0	-3	S 18	100 m	8 Cu 00 from SW	Heavy cont. snow	Heavy snow	51.8	-1.5	-2.9	No	" "	
22	-0.2	-0.2	0	S 24	500 m	8 Cu 00 from W	Mod cont. snow	Mod cont. snow	43.8	0.0	-3.0	No	" "	
23	-1.3	-1.7	-2	W 36	3 km	6 Fs 03 4 As from W	Clouds forming	Clear, high winds	7.0	0.2	-3.2	No		

114 cm on
3.8.74

Table 2 Observations (0900) at Cabramurra (1453 m), Kiandra (1395 m) and Thredbo (1957 m), 17 to 23 July 1974

Date	Station	Cloud amount	Wind (kn)	Weather	DB (°C)	DP (°C)	Max (°C)	Min (°C)	Rain (mm)	Snow depth (cm)
17	Cabramurra	8	NW 9	Rain	3	3	3	1	11	2
	Kiandra								14	
	Thredbo	x	NW 54	Snow (5 cm new)	-1	-1	2	-	5	
18	Cabramurra	8	NW 18		3	0	6	1	49	
	Kiandra	8	W 26		4	2	7	2	31	
	Thredbo	x	NW 49	(Hail)	-1	-1	3	-	30	
19	Cabramurra	8	NNW 18	Rain	-1	0	4	-1	28	3
	Kiandra	x	W 25	Fog (Snow)	-0	-1	5	-1	16	
	Thredbo	x	NW 43	Snow (10 cm new)	-3	-4	0	-4	10	
20	Cabramurra	8	NNW 27	Snow	0	0	-	-	25	8
	Kiandra									
	Thredbo	x	NNW 32	Snow	-4	-4	-2	-	10	
21	Cabramurra									
	Kiandra	x	W 26	Fog	0	0	1	-2	7	15
	Thredbo	x	NW 32	Snow	-3	-4	-2	-	71	
22	Cabramurra	8	NNW 14	Drizzle	1	1	2	-1	40*	22
	Kiandra									
	Thredbo	x	NNE 43	(15 cm new snow)	-3	-4	-2	-	66	
23	Cabramurra	7	NNW 5	(Drizzle)	0	0	2	0	3	20
	Kiandra	5	W 19	Mist	2	0	4	-9	21	
	Thredbo	7	NW 65	Blowing snow	-3	-3	-1	-		

* 48-hour total

It is difficult to estimate the amount of snow that fell during this period. On 18 July there was no snow at Cabramurra and on 22 July, twenty-two centimetres. The snow bulletin, issued each Thursday by the Bureau, gives depths in descriptive terms (light < 20 cm, medium 20-60 cm and heavy > 60 cm). On 18 July, Perisher and Kosciusko Chalet reported a light cover; The Smiggin Holes reported patchy cover. On 25 July the cover was heavy at Perisher and The Smiggin Holes and medium to heavy at Kosciusko Chalet. The last snowfall occurred on 22 or 23 July. It seems reasonable to assume that about 50 to 60 cm of snow fell above 1600 m over the period of this case study. At Falls Creek in Victoria the snowdepth increased by 50 cm in the period 18 to 25 July.

3 to 5 August 1974

Figs 6(a) to (c) are the MSL analyses at 0900 EST on 3, 4 and 5 August 1974 respectively. On 3 August a cold front in a strong westerly gradient was in the area and another was approaching Adelaide. Snow was falling at Cabramurra, Kiandra and Kosciusko Chalet. At Cabramurra, 9 cm had fallen in the past 24 hours and at Kiandra 10 cm.

By 0900 on 4 August, the airstream over the Snowy Mountains area had become southwesterly. An additional 30 cm of snow had accumulated at Cabramurra and 125.5 cm at Kosciusko Chalet. The melted depth of precipitation here was only 31 mm so either the gauge gave an underestimate (Walsh (1961) says that snow gauges grossly underestimate the snowfall in strong wind conditions) or drift snow accumulated at the measuring point. The temperature at the Chalet was -3°C. Over the 24-hour period to this time, the surface gradient wind had been westerly until 2100 EST after which a slow change to southwesterly occurred.

At 0900 on 5 August, the surface gradient wind over the area was southerly. Snow had stopped falling at all of the mountain stations except Thredbo where only 1 mm of melted snow was in the gauge. Only another 8 mm of water had accumulated in the gauge at the Chalet but there was 29 cm more snow on the ground at Cabramurra. The temperature was -8°C at Cabramurra and -7°C at the Chalet. Table 3 gives the 0900 EST observations at Kiandra, Cabramurra, Kosciusko Chalet and Thredbo on 3, 4 and 5 August 1974.

Table 3 0900 observations at Kiandra, Cabramurra, Kosciusko Chalet and Thredbo, 3 to 5 August 1974

Date	Station	Cloud amount (eighths)	Wind (kn)	Weather	DB (°C)	WB (°C)	Max (°C)	Min (°C)	Rain (mm)	Snow depth (cm)
3	Kiandra	Sky obs	W 9	Thunderstorm with snow	-1	-1	+5	-6	15	10 cm new snow
	Cabramurra	8	WNW18	Snow	0	0	+1	-3	27	30
	Kosciusko Chalet	8	SW 26	Snow	-1	-2	-2	-2	17	114.5
	Thredbo			No observation						
4	Kiandra	Sky obs	W 10	Snow	0	0	+1	-2	49	76
	Cabramurra	8	SW 15	Unknown	-1	-1	0	-2	unknown	60
	Kosciusko Chalet	8	SW 22	Snow	-3	-5	0	-4	31	240
	Thredbo	Sky obs	WSW32	Snow	-4	-4	-2	-5	10	24+
5	Kiandra			No observation						
	Cabramurra	1	Calm	Past snow	-8	-8	0	-10	12*	89
	Kosciusko Chalet	7	SW 16	Past snow	-7	-9	-2	-10	8	unknown
	Thredbo	8	SW 16	Snow	-9	-11	-2	-12	1	unknown

+ Probably a depth of new snow

* 48 hour total

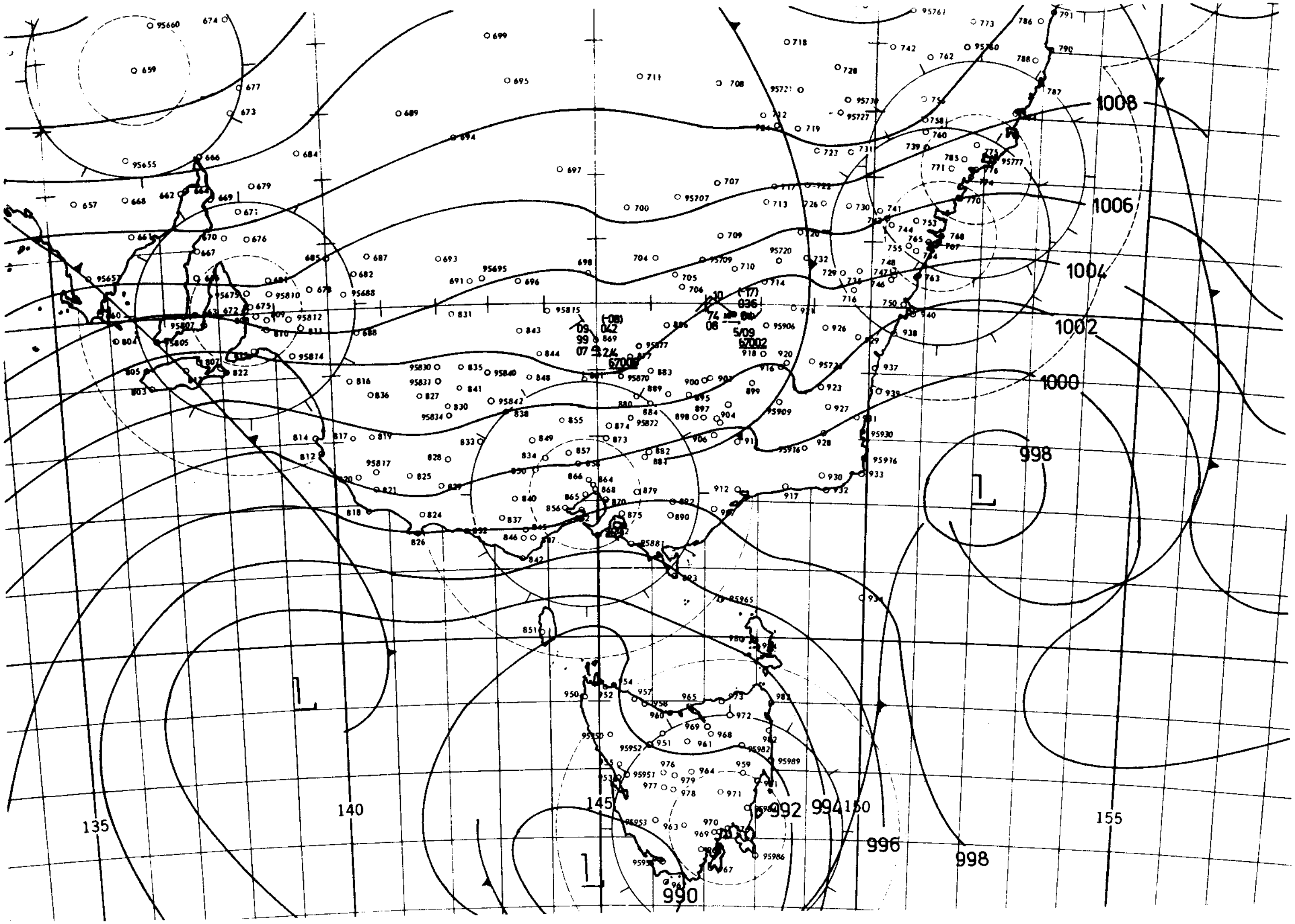

Fig 6(a) MSL synoptic chart 0900 EST 3 August 1974

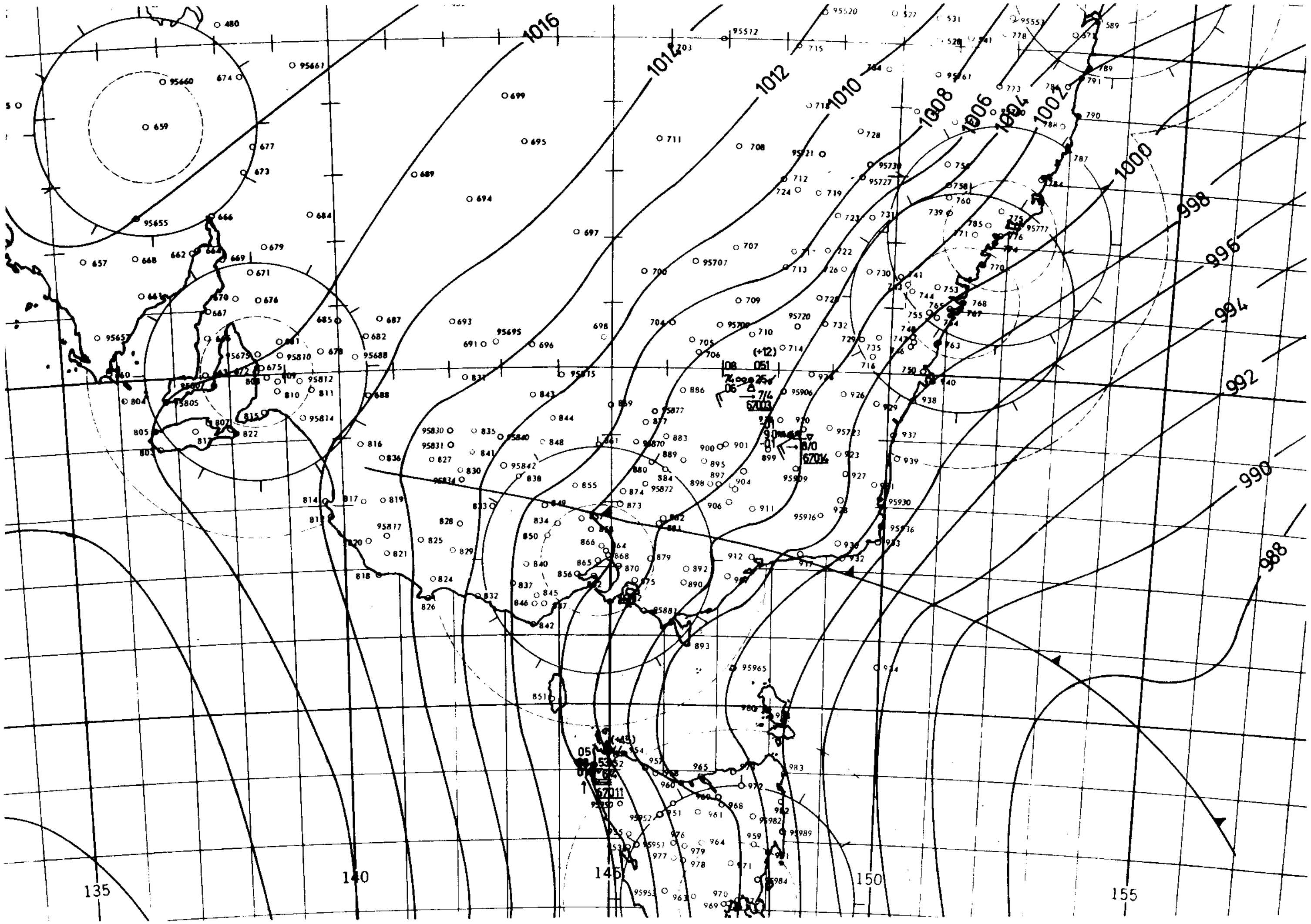

Fig 6(b) MSL synoptic chart 0900 EST 4 August 1974

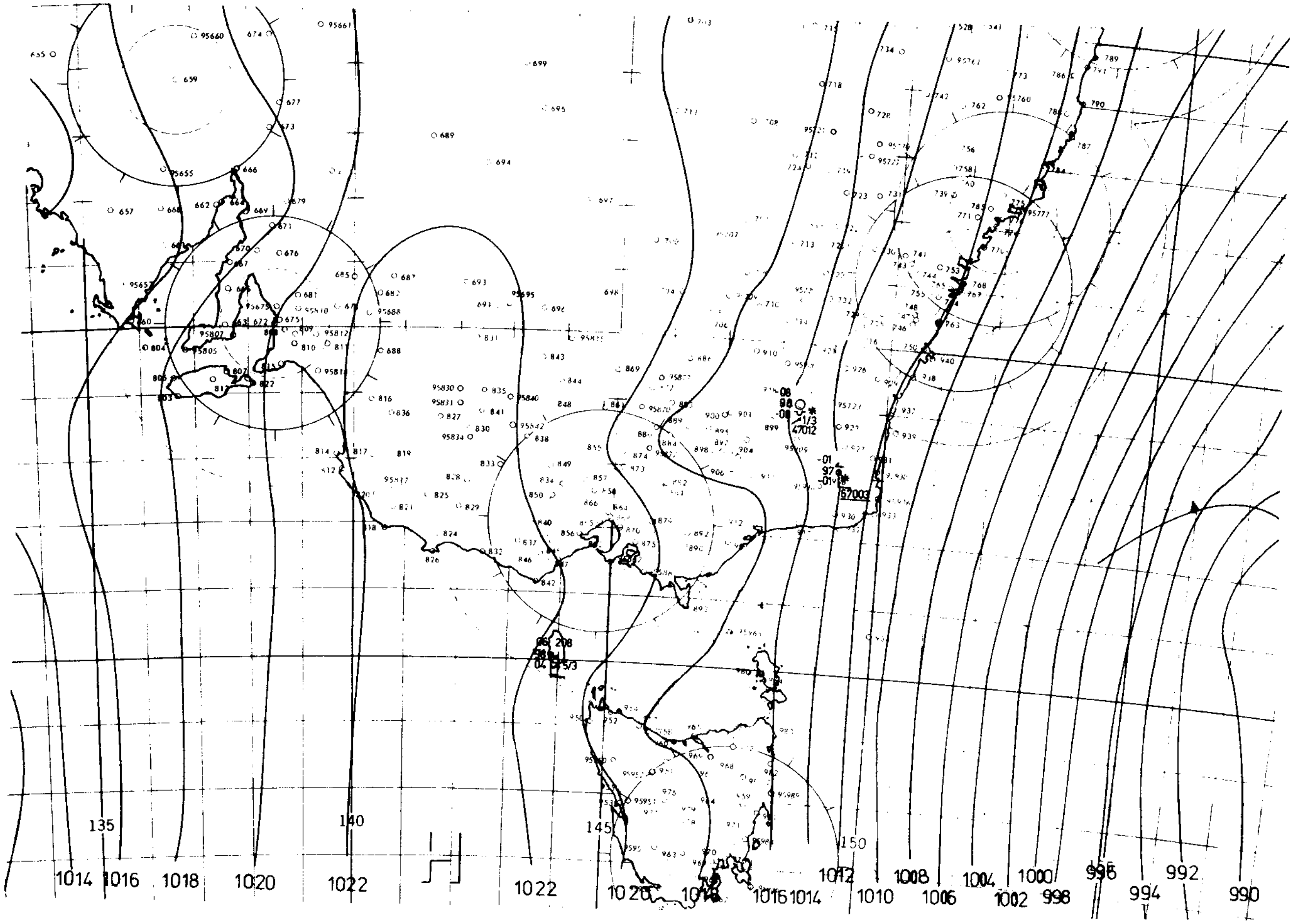

Fig 6(c) Synoptic chart 0900 EST 5 August 1974

At the 850 mb level the 0900 EST wind velocities just to the west of the Snowy Mountains were 280° 40 kn on 3 August, 220° 35 kn on 4 August and 180° 15 kn on 5 August.

It may be concluded that although a very cold southerly stream had become established by 5 August, most of the snow associated with the cold outbreak occurred before the wind had backed to the southwest on 4 August, and that very little snow fell on the higher parts of the mountains while the cold southerly windstream was affecting the area.

VARIATIONS IN WATER CONTENT AND DENSITY OF THE SNOWPACK

The Snowy Mountains Hydro-electric Authority maintained snow courses in the Snowy Mountains area between 1954 and 1968. Records of observations are held by the Bureau of Meteorology. Average snow depth and average water content were measured at snow courses during this period. The frequency of observation was weekly at some snow courses but less frequent at most. The number of sampling points at snow courses varied between 3 and 15. Fig 1 shows the location of snow courses mentioned in this study.

At Spencers Creek (1829 m), observations were made weekly and seven sampling points were used. Fig 7(a) shows the average water content of the snowpack at Spencers Creek in the years 1964 to 1968 inclusive. Heavy snowfalls occurred in 1964 and 1968. Data are also available for the period 1954 to 1963, but these are not reproduced here. In 1954, the year when the water content of the snowpack was least, the maximum water content of the snow was just over 40 cm. The greatest water content of the snow occurred in 1964 when almost 166 cm was measured.

According to the meteorological glossary, 30 cm of freshly fallen snow has about the same water content as 25 mm of rainfall. Presumably this refers to snowflakes, one would expect that freshly fallen graupel would have a higher water content. The density of fallen snow is defined as the water content divided by the snowdepth. Snowpacks usually increase in density because of wind packing and the weight of the snow. As the snowdepth increases during the year the density increases. The density of the snowpack at Spencers Creek in 1964, a year of heavy snowfalls, and 1965, a year of light snowfalls, is shown in Fig 7(b).

THE RELATIONSHIP BETWEEN THE ATMOSPHERIC CIRCULATION AND PRECIPITATION

Correlations between a circulation index L and snowfall

Pittock (1973) defines a circulation index, L, as the mean monthly latitude of the high pressure belt. He calculated the values of L over the thirty year period 1941 to 1970 from the mean monthly surface pressures reduced to mean sea level, for a chain of eleven stations down the east coast of Australia from Cairns (16.9°S) to Cape Bruny (43.5°S). He found that mean annual values correlated significantly with district mean annual rainfall in parts of Australia. Significant correlations of rainfall over shorter periods with L values were also found.

Low L values should be associated with strong zonal flow to the south of the latitude L. Hence one would expect a negative correlation between L values and snowfalls over the Snowy Mountains. The change in water content of the snowpack in July and August at Spencers Creek (1830 m) and Cootapatamba (2010 m) snow courses was correlated with L values in these months using 15 and 14 years of data respectively. Table 4 shows the correlation coefficients.

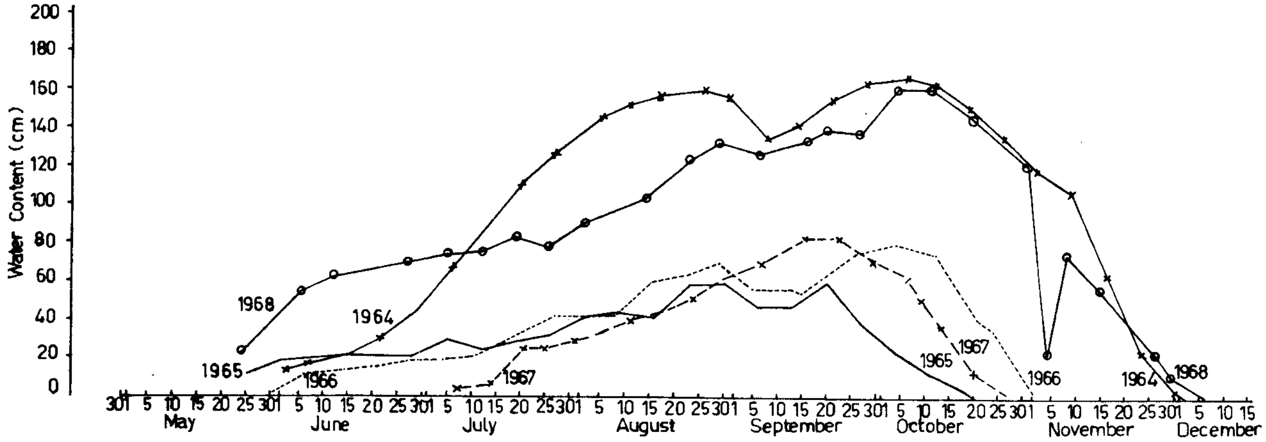

Fig 7(a) Water content of the snowpack at Spencers Creek 1964-1968

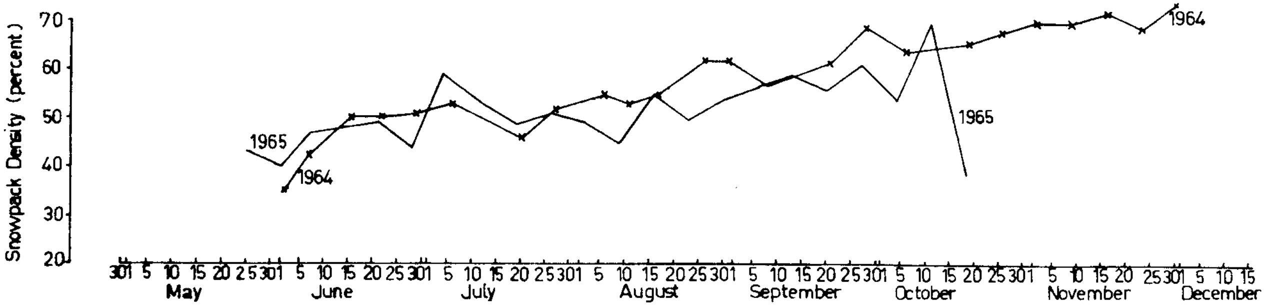

Fig 7(b) Density of the snowpack at Spencers Creek 1964-1965

Table 4 Correlations, r, between the mean latitude, L, of the subtropical high pressure belt and the change in the water content of the snowpack. N is the number of years of data

		r	
Snow course	N	July	August
Spencers Creek (1830 m)	15	-0.38	-0.36
Cootapatamba (2010 m)	14	-0.37	-0.39

Although on a monthly basis, the value of L affects the change in the water content of the snowpack, the correlation is not high. It cannot be inferred from these figures that strong zonal flow is the major cause of heavy snowfalls in either July or August.

Correlating the average water content of the snowpack in the months July to October inclusive ($\overline{W}_{J,O}$), with the average L value in these months ($L_{J,O}$), produced correlation coefficients of -0.79, using 15 years of Spencers Creek data and -0.63, using 14 years of Cootapatamba data. The first value is significant at the 0.1 per-cent level of chance probability and the second at the 2 per cent level. In snow seasons when small $L_{J,O}$ values occur, strong zonal flow predominates, deep snowpacks accumulate and last well into spring. Fig 8 shows the year to year variations in $L_{J,O}$ and $\overline{W}_{J,O}$ values at Spencers Creek. Both exhibit a biennial oscillation and $\overline{W}_{J,O}$ values have marked peaks at four year intervals. On the basis of this figure, qualitative estimates of $\overline{W}_{J,O}$ can be made from the $L_{J,O}$ values in years when no snow-data are available; i.e., in 1946 and 1951 deep snowpacks may have formed and 1944, 1950 and 1952 probably had light snow covers.

Quantitative values can be estimated from the regression equation

$$\overline{W}_{J,O} = -10.31\ L_{J,O} + 374.1$$

where $\overline{W}_{J,O}$ is in centimetres.

At high elevations, most of the snow that falls during the winter remains on the ground and is not melted until after the maximum snowpack water content (W_{MAX}) is reached. The W_{MAX} value should give a reasonable estimate of the amount of snow that falls or is blown to the observing site during the winter and spring. This value would be an underestimate because of snowmelt before the W_{MAX} is reached and snowfall or snowdrift after this time.

Fig 9 shows the maximum water content of the snowpack at snow courses, ranging in elevation from 1620 m to 2010 m, for varying periods in the years 1954 to 1968. Mean June to October L values are also shown. A biennial oscillation is again evident in both the L and the W_{MAX} values. Very high W_{MAX} values occurred at intervals of four years. Wilkinsons Valley and Cootapatamba are at about the same elevation but the W_{MAX} value in most years was greatest at Wilkinsons Valley. The difference was particularly marked in years when heavy snowfalls occurred. Both of these snow courses are on the western side of the main ridgeline of the Snowy Mountains, however Wilkinsons Valley is on the eastern side of a secondary ridge which originates at Mt Townsend. More drifting snow would accumulate at Wilkinsons Valley than at Cootapatamba. Lake Albina, on the northern slopes of Mt Townsend, has W_{MAX} values which are close to those at Cootapatamba and Wilkinsons Valley in

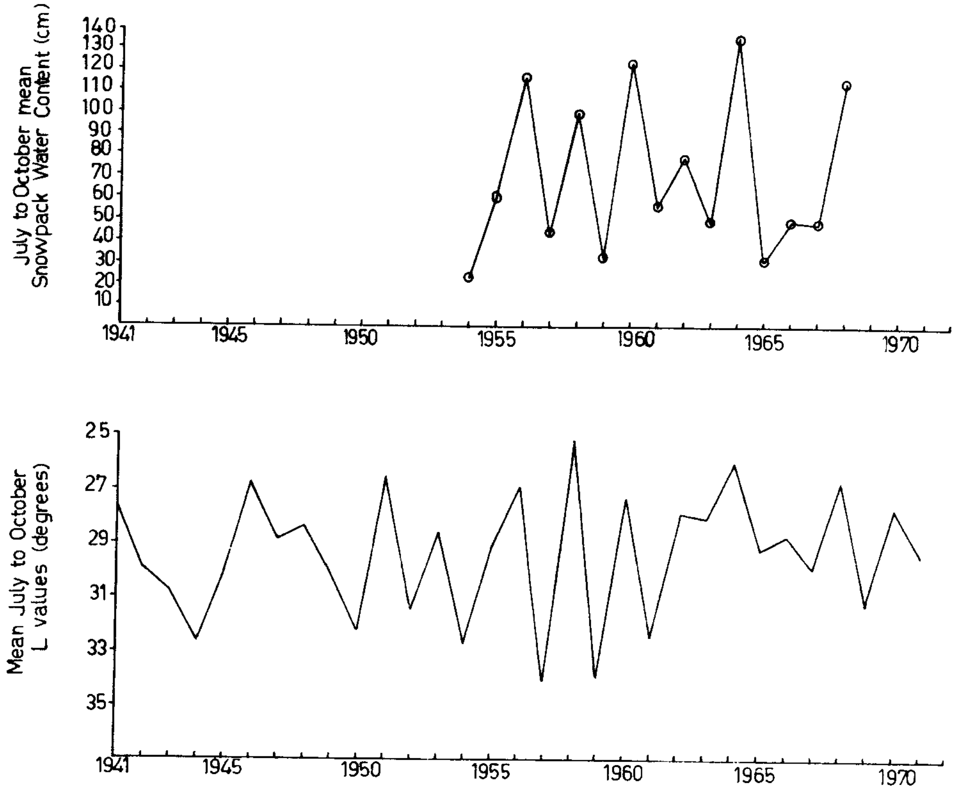

Fig 8 July to October mean snowpack water content (cm) at Spencers Creek and mean July to October L values (degrees)

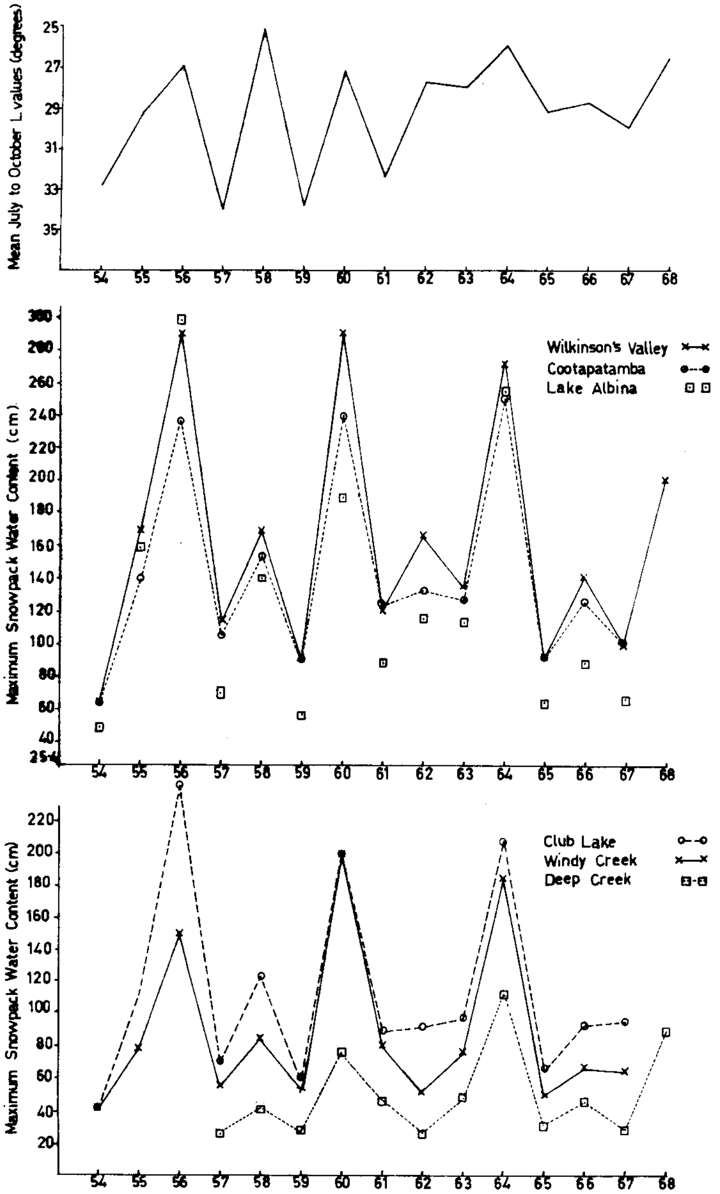

Fig 9 Maximum water content of the snowpack at six snow courses and L values in the years 1954 to 1968

seasons with heavy snowfalls, when average daily cloud cover would be high. In seasons with light snow cover, the water content of the snowpack is usually much less at Lake Albina than at the other two snow courses. In those seasons, average daily cloud cover would be low and, as Lake Albina snow course is on a slope facing north, it would receive higher total radiation per unit area than the other two sites that face south; hence greater snowmelt would occur at Lake Albina. Club Lake and Windy Creek are on opposite sides of the main ridgeline and at about the same elevation. Club Lake, on the eastern side of the range, has W_{MAX} values which are usually well in excess of those at Windy Creek.

Table 5 shows the correlations between W_{MAX} values at seven snow courses and mean L values calculated over various periods.

Table 5 Correlations, r, between maximum water content of snowpack (W max) and mean L values over various periods. N is the number of years of data and P is the probability of occurrence of the given values of r by chance.

Snow course	Elevation (m)	Number of years of data	Period over which mean L value was calculated					
			Jul-Sep		Jul-Oct		Jun-Oct	
			r	P	r	P	r	P
Deep Creek	1620	12	-0.57	~0.05	-0.57	0.05	-0.63	0.05
Club Lake	1800	14	-0.69	0.01	-0.69	0.01	-0.73	0.01
Thredbo	1800	14	-0.71	0.01	-0.71	0.01	-0.78	0.001
Windy Creek	1800	14	-0.63	0.02	-0.57	0.05	-0.56	0.05
Spencers Creek	1830	15	-0.71	0.001	-0.78	0.001	-0.80	0.001
Cootapatamba	2010	14	-0.68	0.01	-0.70	0.01	-0.72	0.01
Wilkinsons Valley	2010	15	-0.69	0.01	-0.71	0.01	-0.74	0.01

All of the correlation coefficients are significant at $P \leqslant 0.05$. At all snow courses except Windy Creek the most significant correlations occurred when the mean L values over the period June to October were used. Snow courses near the main ridge line or on the eastern side have more significant correlations than those on the western side (Windy Creek and Deep Creek).

Mean January to April L values were correlated with mean June to October L values to determine whether the circulation in the later period could be predicted from the L value in the first. However the value of r was not significant.

Correlations between L and district average rainfall on the New South Wales coast

Priestley (1964) compared rainfall along the NSW coast with sea surface temperatures at several points near the coast. He concluded, 'It seems then to have been established, from the overall consistency of the results, that there is a positive association between monthly anomalies in rainfall and sea surface temperature along the NSW coast. However the practical aspiration of using this as a help in predicting monthly rainfall is not greatly furthered by values "(of r)" around +0.15 to +0.20 such as have been observed at one month lag in the appropriate sense'. He also concluded that results would have been more positive if better sea surface temperature data had been available a hundred or so miles from the coast.

The east Australian current flows southward, adjacent to the NSW coast. If a period of strong easterly winds prevailed over the Tasman Sea one would expect that, due to the Ekman drift, the coastal current would be strengthened producing higher than normal sea surface temperatures near the coast and higher than normal rainfall in coastal areas. Similarly, it might be argued that a period of strong westerly flow over the southern Tasman Sea would produce an equatorward transport of cold water. Consequently the east Australian current would be weaker, resulting in lower than normal sea surface temperatures and hence lower than normal rainfall along the NSW coast. This reasoning is doubtless an oversimplification of the situation.

Hamon (1965) discussed the east Australian current using the results of eight cruises between 1960 and 1964. He found that the circulation in the area was complex and variable. 'The south flowing east Australian current leaves the coast in latitude 33°S to 34°S and frequently returns towards the north or northeast, as had been found earlier (Hamon, 1961). Anticyclonic eddies about 250 km in diameter appear to form at 34°S and move southward.' The eddies may be caused by the wind and would be affected by it, so the effect on sea surface temperatures of an anomalous atmospheric circulation pattern would be complex, especially south of about 34°S.

It was mentioned earlier that Pittock found significant correlations between rainfall and mean L values calculated over periods ranging from one month to one year. Table 6 shows the correlation between mean L values in the period January to June, inclusive, and district average rainfall in NSW coastal districts over the same period. All districts, with the exception of the South Coast and Hunter districts have r values significant at $P \geqslant 0.10$.

Some lag correlations

Mean L values in the months June to October were correlated with mean L values in the first three and six months of the following year. Values calculated were not significant. Plotting the corresponding values on a scatter diagram confirmed that there was little correlation. However one suspects, from inspection of the diagrams, that two distributions existed.

Correlating the mean June to October L values with the January to June district average rainfall in the next year (see Table 6) produced r values that were not significant; however, using the W_{MAX} value at Wilkinsons Valley instead of the mean L value, produced r values that in most cases were more significant. Values of r of -0.42 and -0.48 were obtained for the Metropolitan East and Hunter districts. In these districts, years with high W_{MAX} values were followed by low rainfall in January to June of the next year. The maximum water content of the snowpack on the higher parts of the Snowy Mountains may be a better circulation index in the winter and spring months than a mean L value.

Correlating the district average rainfall over the first six months of the year with average L values in the first six months of the previous year (using 15 years of data) produced r values of -0.35 for the South Coast and -0.33 for the Illawarra rainfall districts. Both of these values are more significant than those obtained for the same districts using the mean June to October L values.

CONCLUSIONS

The synoptic situation that produces much of the snowfall over the Snowy Mountains area in winter and spring is a strong westerly stream. Although cold southerly airstreams produce snowfalls at very low elevations they are usually of short duration and do not produce heavy snowfalls on the higher parts of the mountains.

Table 6 Correlations, r, between the parameters in the first column of the table. r = 0.44 is significant at P = 0.10 and r = 0.59 at P = 0.02. N = 15

Parameters correlated	Rainfall district						
	South Coast	Illawarra	Metropolitan East	Hunter	Manning	Lower North Coast	Upper North Coast
Mean Jan-Jun L value and Jan-Jun dist. av. rainfall	0.32	0.44	0.48	0.22	0.48	0.58	0.63
Mean Jun-Oct L value & Jan-Jun dist. av. rainfall in next year	-0.09	0.00	0.12	0.20	0.06	0.06	0.05
Wilkinsons Valley max. snowpack water content and Jan-Jun dist. av. rainfall in next year	-0.05	-0.18	-0.42	-0.48	-0.27	-0.22	-0.25
Mean Jan-Jun L value & Jan-Jun rainfall next year	-0.35	-0.33	-0.19	0.05	-0.07	0.06	0.04

Powder snow crystals and graupel fall on the mountains at higher elevations than raindrops that originate at the same point, because of their low terminal velocities. Much of the snow formed on the windward slopes falls on the lee side of the range.

The annual variation in the maximum water content of the snowpack (W_{MAX}) is large. There was a biennial oscillation in W_{MAX} values over the period 1955 to 1968 inclusive, with large W_{MAX} values occurring at four yearly intervals. W_{MAX} values were found to correlate significantly with mean values of a circulation index, L, calculated over periods ranging from three to five months in the months June to October. Generally the higher snow courses on the eastern side of the range showed the most significant values. Mean June to October L values from 1941 to 1951 do not exhibit a biennial oscillation or peaks at four yearly intervals, so it would be unwise to extrapolate forward the 1955 to 1968 pattern and assume that heavy snowfalls will occur at four yearly intervals.

No connection was found between mean L values over the period January to April and mean L values over the period June to October.

Lag correlations were found between W_{MAX} at Wilkinsons Valley and Metropolitan East and Hunter district average rainfall in the first six months of the next year. Values were significant at $P \approx 0.10$. In these districts, years with high W_{MAX} values were followed by low rainfall in the first six months of the next year. Less significant lag correlations were found between mean January to June L values and district average rainfall in the same six months of the next year in the South Coast and Illawarra rainfall districts.

ACKNOWLEDGMENTS

Correlation coefficients were computed by Val Lettau. Cyndi Gallagher prepared the diagrams.

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APPENDIX

Definition of McGrath Snow Index

The McGrath Snow Index (MSI) is defined by

$$\mathrm{MSI} = \theta_{SW(850)} + \left(\frac{F}{10}\right) - 70 - T_{(500)}$$

where $\theta_{SW(850)}$ = 850 mb pseudo wet bulb temperature (^{o}C)

F = freezing level (mb)

T_{500} = 500 mb temperature(^{o}C)

Table 7 The relationship between MSI values, snowfall and the lowest snowfall elevation

MSI	Snowfall intensity	Lowest snowfall elevation (m)
40-44	Light	1500
45-49	Light to moderate	1200
$\geqslant$ 50	Moderate to heavy	900

Note: If the MSI is near 60, snow as low as 600 m can be anticipated.