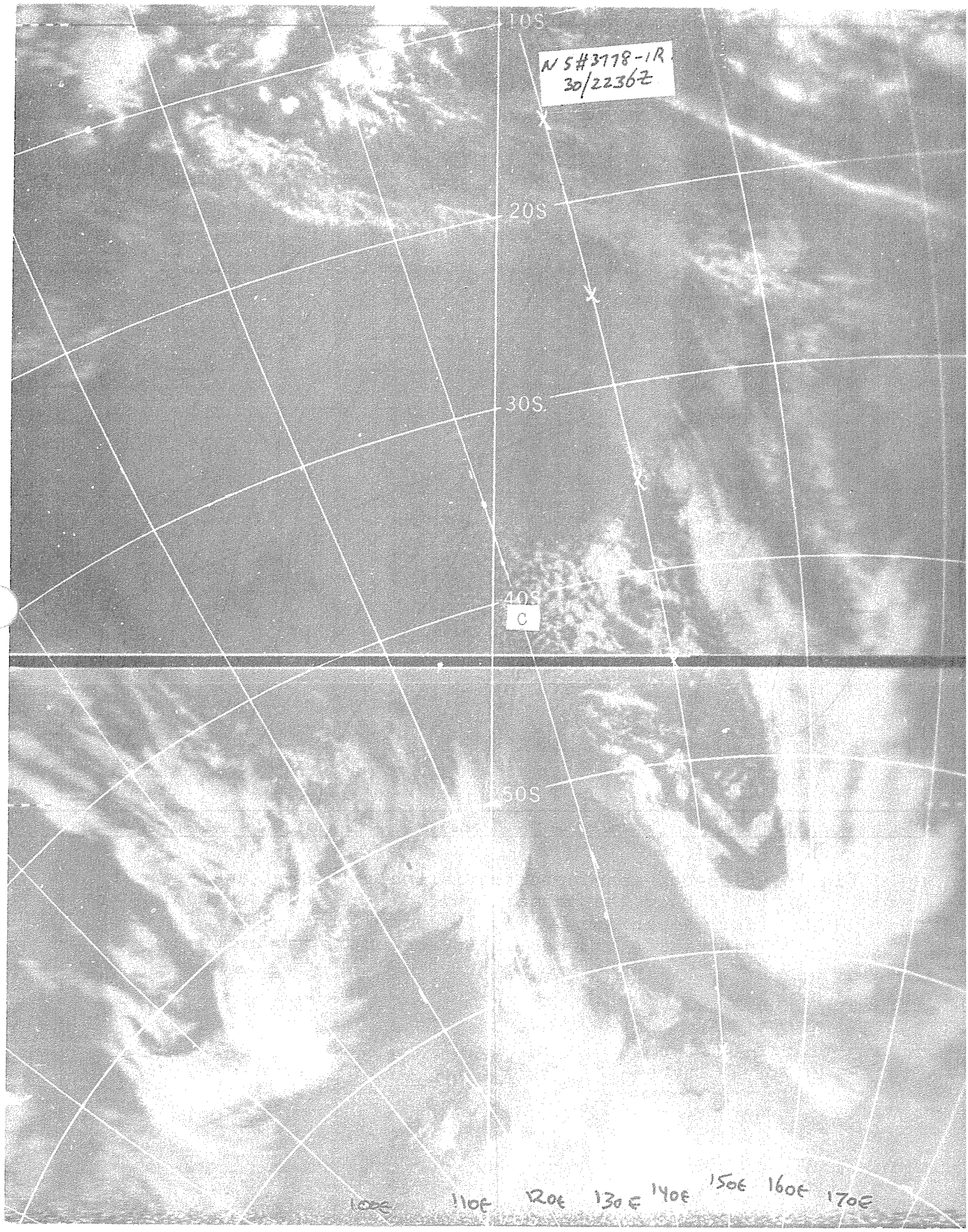

Fig 13. Infrared satellite cloud imagery of the Australian region for 2236 GMT 30 May 1977

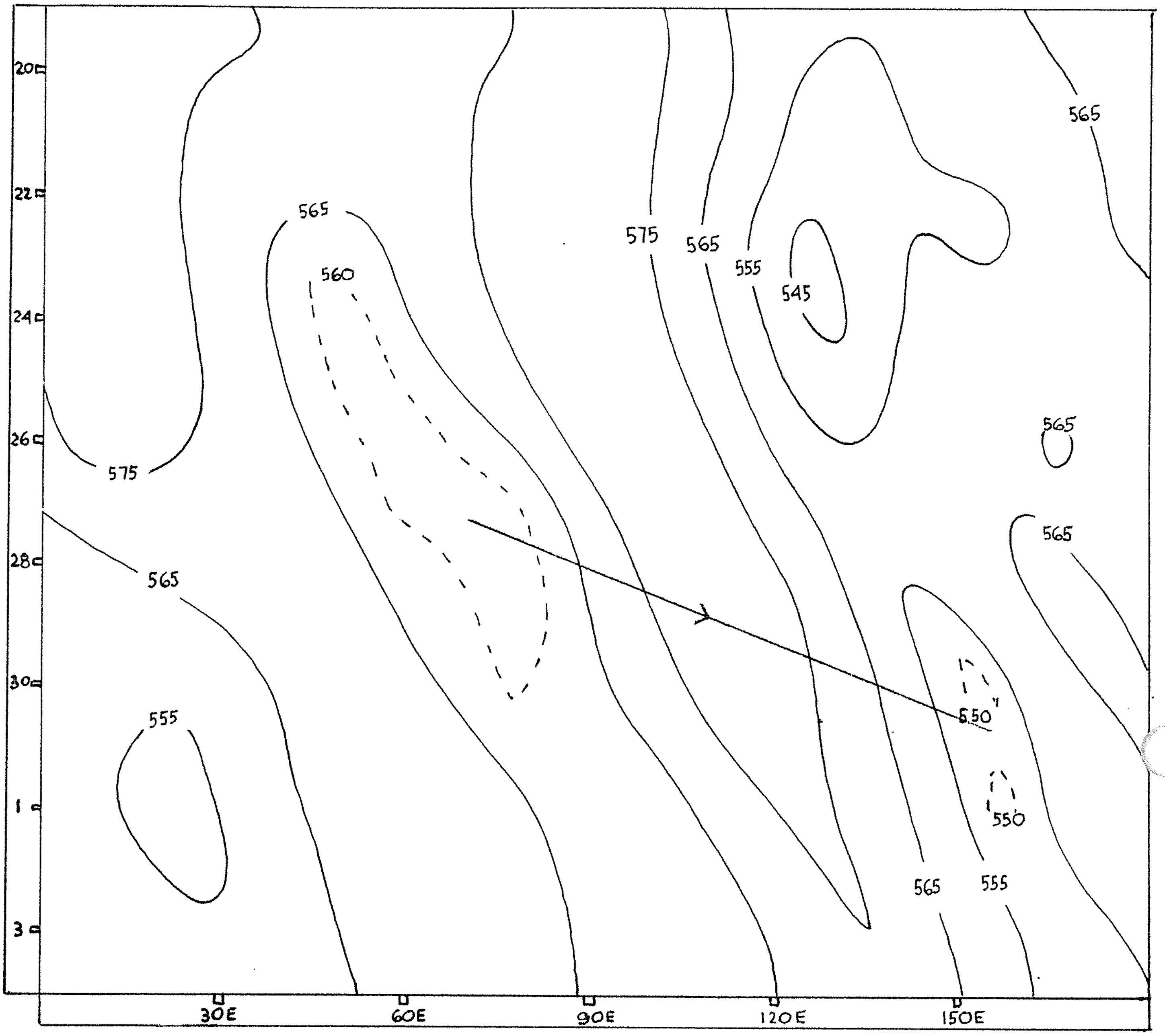

Fig 14. Five-day-mean geopctential height (dm) analysis at 45°S over the eastern half of the southern hemisphere for the period 20 May 1977 to 3 June 1977. The energy dispersion process is indicated by the arrow.

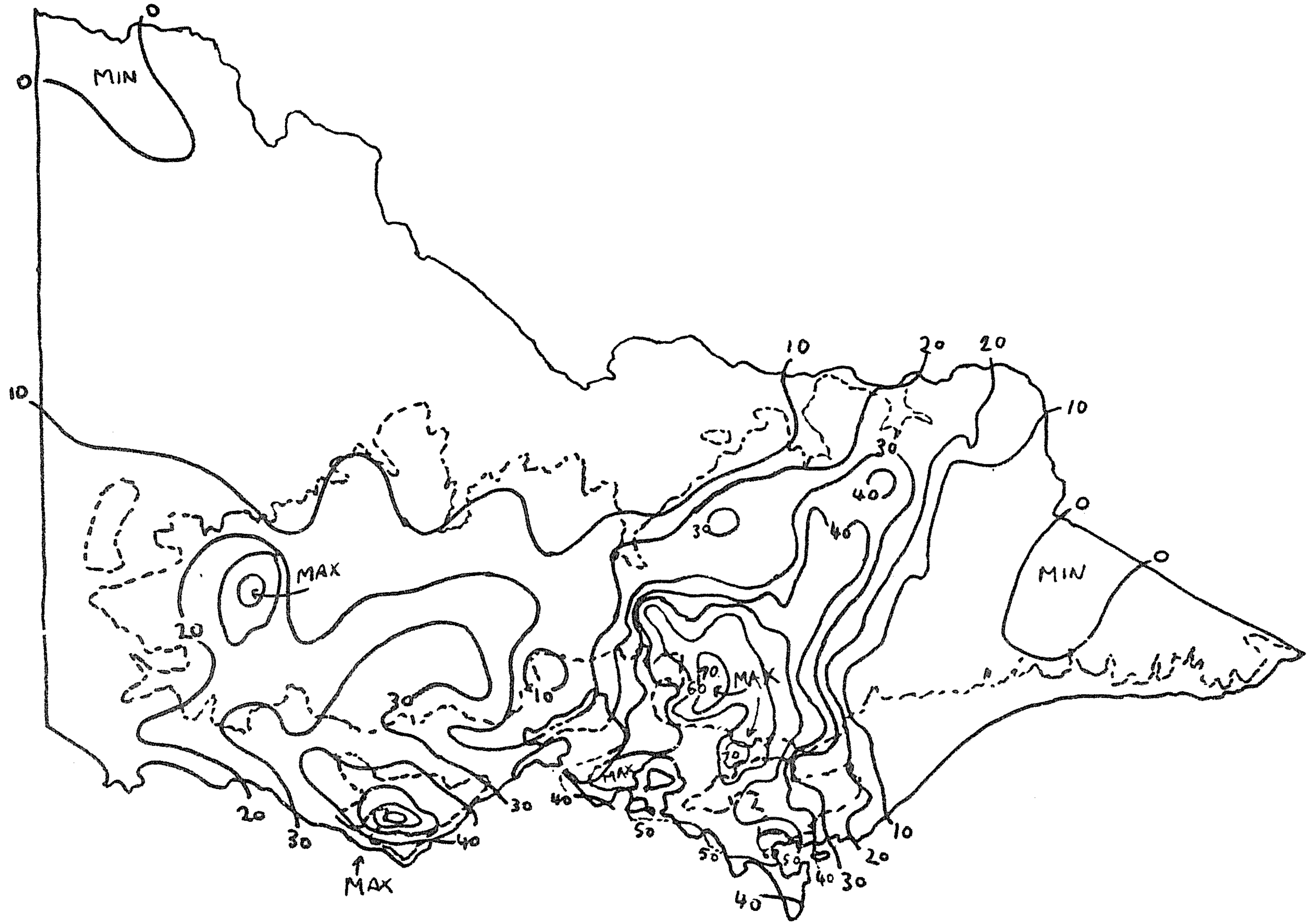

Fig 15. Isohyet map of Victoria - 48 hr to 0900 EST 1 June 1977 rainfall

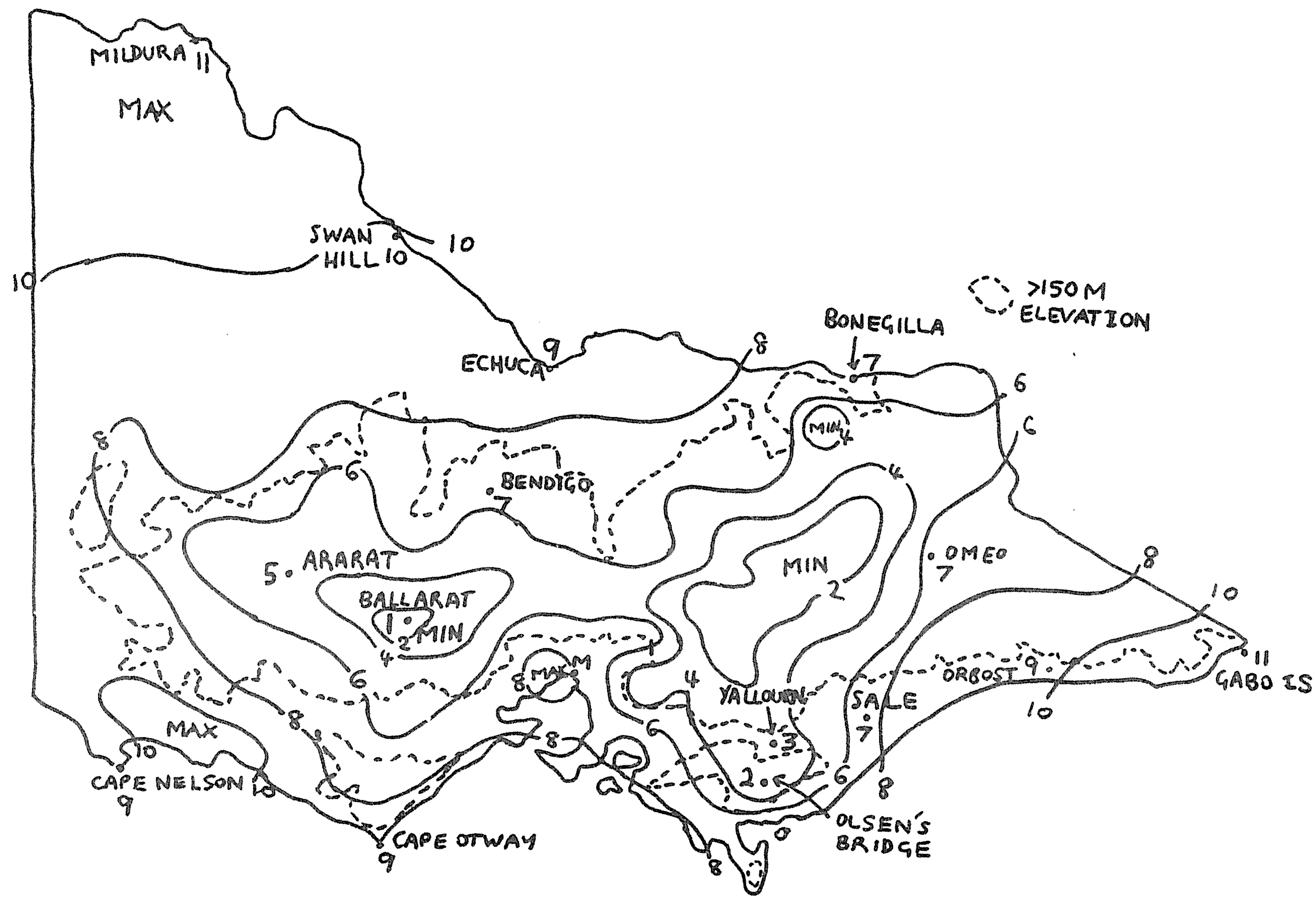

Fig 16. Maximum temperatures - Victoria; 6 hr to 1500 EST

31 May 1977

Table 1 : A summary of Victorian Snow Reports : 31 May 1977

Lowest Stations, Name, elevation (m), extent	Major Centres Name, elevation (m), extent	Stations with Heaviest Falls Name, elevation (m), extent
Northern Country and North Central (Areas 81 and 88)		
Joyce's Creek - 229 - Light snow	Bendigo - 226 - had light snow	Rubicon -838 - reported 48 cm of snow
Murrindindi - 225	Trentham - 686 - 'good ground covering'	
Buxton - 259	Kyneton - 509 - snow settled	
Wimmera (Areas 78 and 79)		
Great Western - 244	Stawell - 231 - light snow	Reed's Lookout - up to 20 cm
Stawell - 231 - snow, melting as it hit the ground		Grampians -680m - 'The Victoria Range viewed from the Henty Highway was 1/2 to 1/3 covered in snow.'
Hall's Gap - 213		
West Gippsland (Area 85)		
Latrobe Valley		
Traralgon - 46	Korumburra - 229 - 'about 15 cm of snow'	Budgeree East - 442 - 30/45 cm snow
Moe - 62 'about 5 cm'	Warragul - 116 - about 5 cm	Mt Baw Baw - 1600 - had 45 cm snow
Morwell - 82	Drouin - 140 - sleet	Balook - 640 - had 23 cm snow
Trafalgar - 50	Yallourn - 153 - 30 cm snow reported	Yallourn Golf Club - 120 - about 15 cm snow
	Walhalla - 336 - 5/10 cm	
Remainder:		
Yarram - 18		
Drouin - 140 - sleet		
North East (areas 82 and 83)		
Tallangatta - 198	Strathbogie - 508 - 'Light snow'	Mt Hotham - 2000 - 60/90 cm
Everton - 207	Omeo - 649 - " "	Mt Buffalo - 1850 - 30 cm
Myrtleford - 225	Beechworth - 549 - " "	Stanley/
Gapsted - 228	Glenrowan - 305 - 'One report of snow'	Yackandandah - 300 to 700 - 'heavier falls'
Licola - 207	Bright - 305 - Light snow	Wood's Point - 685 - heavy
	Corryong - 320 - " "	Timbertop - 610 - heavy
	Mt Beauty - 366 - " "	Strathbogie Nth - 569 - about 15 cm

Lowest Stations, Name, elevation (m), extent	Major Centres Name, elevation (m), extent	Stations with Heaviest Falls Name, elevation (m), extent
East Gippsland (Area 84)		
The only places reporting snow were:	All falls were light.	
Dargo - 207		
Tongio - 853		
Brookville (Swift's Creek) - 610		
Western District (Areas 89 and 90)		
Heywood - 27	Ballarat - 459 - about 5 cm snow	Heaviest falls in the Otways
Warrnambool - 21 - sleet	Rokewood - 175	Beech Forest - 490 - heavy falls
Wando Heights near Casterton - 150	Skipton - 288	Dereel - 335 - about 15 cm of snow
Wannon Reserve near Hamilton - 160	Beauford - 387 - light snow	
Leyton - 122	Camperdown - 165 - melting on ground	
	Ararat - 332	
Central District (Areas 86 and 87)		
Glen Waverley - 137	Powelltown - 189	Narbethong - about 400 m - Maroondah Highway closed and covered by about 25 cm of snow.
Somerville - 68	Ballan - 509 - 2/5 cm of snow on ground	
Athlone - 84	Red Hill - 182 - Light snow	
Coonil - 91	Macedon - 503	Mt Macedon - 762 - 'covered in a blanket of white snow'
	Olinda - 488 - 20 cm deep in places	
	Romsey - 488	

- The lower elevations of stations reporting snow were around 150 to 200 metres in most districts. However, there were some exceptional falls at near sea level in the southern districts, particularly in West Gippsland.

Snowfall in the Latrobe Valley - A discussion

Snowfall was extensive in the Latrobe Valley (mostly 50 to 100 m elevation). Fifteen centimetres fell at Yallourn Golf Club. Snow fell as far down the valley as Morwell (see Table 1). Snow in West Gippsland, outside the Latrobe Valley, fell down to a level of about 150 m elevation. Reports from low elevation stations such as Yarram were the exception. Snowfall in the Latrobe Valley was much heavier than stations of a similar elevation elsewhere in Victoria. Figure 17 shows quite high precipitation reading in this area. This higher amount of precipitation is part of the explanation.

However, stations like Drouin, just outside the Latrobe Valley and Warragul at the head of the Latrobe Valley had similarly large precipitation totals to stations in the valley and yet received less snowfall. Apparently there is some local effect involved in this situation to promote snowfall in the Latrobe Valley.

From Fig. 17 a rainfall maximum was centred near Warragul at the head of the Valley. This position of the maximum is not surprising in the moderate west to southwest airstream of this situation. Topography suggests that this flow would converge here. Also, the temperature trace (Fig. 3), and synoptic observations indicate that this rainfall would have been of a strongly convective nature. We suggest that this convective area would have encouraged low-level snowfalls in the Latrobe Valley. Downdraughts from the convective area would approach the saturated adiabat temperature and be channelled down the valley by the southwest to westerly airstream. Thus the lower levels of the atmosphere in the Latrobe Valley would be cooler than otherwise, and therefore snow would be able to penetrate to lower levels within the valley than outside.

This allowance for the temperature trace to approach the saturated adiabat during precipitation (and therefore a lowering of the freezing level) is one of the factors mentioned by Lumb (1961, 1963) and Boyden (1964) in relation to precipitation encouraging the downwards penetration of snow. In other words, this effect is the cooling of the atmosphere by the latent heat of evaporation. Because of this effect, the 'wet bulb freezing level' is thought to relate well to snowfall-levels (Lumb 1961, 1963).

Returning to the suggestion that the large amount of precipitation is part of the explanation, it is worth presenting a resumé of some of the ways in which downward penetration of snow below the freezing level is encouraged by precipitation.

Initially one would expect a linear effect, i.e. with the fraction of precipitation as snow at a station remaining constant. Therefore more precipitation would imply proportionally more snow. However, a number of factors further encourage snowfall in heavy precipitation. Lumb (1960) and Boyden (1964) refer to further lowering of the freezing level due to the effect of the the latent heat of fusion as the snow melts in a saturated atmosphere, thus enabling snow to fall to a lower level. Lumb (1963) also

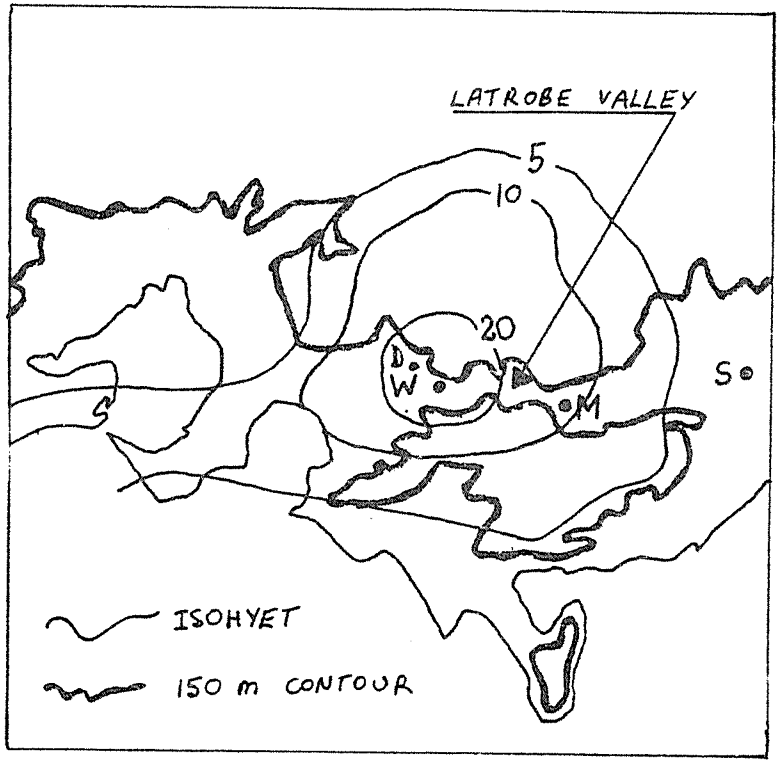

Fig 17. Isohyetal analysis of rainfall (mm) recorded between 0900 and 1500 EST 31 May 1977 over the Latrobe Valley

W = WARRAGUL

M = MORWELL

S = SALE

D - DROUIN

shows that the downward penetration of snow below the freezing level could be expected to increase as the intensity of precipitation increases, i.e. the larger the snowflake the further it falls before completely melting, intensity being related to drop size (Gunn and Marshall 1958).

Lumb (1961, 1963) and Boyden (1964) also consider that snow accompanying showery precipitation falls to a lower level than snow accompanying non-showery precipitation. However Lowndes et al. (1974) in an analysis of snowfall data, could find no statistically conclusive differences in snowfall levels.

Lumb (1961), in an analysis of the levels to which snow could fall, found that during heavy precipitation falls to the 4.5°C wet bulb level were possible, albeit rare. The Latrobe Valley event easily comes inside this criterion when the Laverton temperature trace (Fig. 3) is considered.

Nevertheless the Latrobe Valley snowfall is still fairly exceptional. Fig. 1 indicates that it is reasonable to assume Laverton's temperature trace can be used to calculate conditional probabilities of precipitation being in the form of snow over the Latrobe Valley (see following section). Techniques used by Lowndes et al. (1974) and Boyden (1964) employing the wet bulb freezing level as an indicator show the conditional probability at this elevation (about 80 to 100 metres) to be just under ten per cent whereas the 1000-900 mb adjusted thickness used as an indicator gives a level of near ten per cent. From the earlier discussion on precipitation lowering of the freezing level, the use of Laverton's trace could be misleading. However, Lowndes et al. (1974) and Boyden (1964) in deriving these probability prediction systems would not have had a sounding at each station and would have used some approximation. Therefore these probability levels seem appropriate and are confirmed in a rough manner in the following section.

PERFORMANCE OF SNOW PREDICTORS

A number of parameters can be used for predicting snow. Lumb (1961), Lowndes et al. (1974), Boyden (1964) and Glahn and Bocchiere (1975) have used parameters such as dry bulb freezing level, wet bulb freezing level, 1000-850 mb thickness, 1000-850 mb adjusted thickness, 1000-900 mb adjusted thickness, 850 mb temperature and also boundary layer potential temperature. Some methods involving these parameters produce a conditional probability that if precipitation occurs it will snow rather than rain (see Table 2 and 3).

Surface dew-point and temperature have also been considered as indicators of snowfall by Booth (1970, 1973) and Boyden (1964), but Boyden considers them to be of limited use because of difficulty in forecasting them. Boyden (1964) considered the best indicator to be the 'dry bulb freezing level'. Lumb (1961, 1963) and Lowndes et al. (1974) consider wet bulb freezing level as an important indicator as it allows for the freezing level to fall, due to the latent heat of evaporation. In fact, of the indicators they examined Lowndes et al (1974) considered wet bulb freezing level to be the most efficient indicator.

Boyden (1964) also made the important point that poorer results could be expected with coarser methods such as the 1000-500 mb and 1000-700 mb thickness, as most of these layers were above the freezing level and therefore would bear less relation to occurrence of snow. For example, a temperature trace with a lot of warming above 600 mb could give snowfall at a relatively high thickness value.

Glahn and Bocchiere (1975) used 1000-500 mb thickness, 850 mb temperature and boundary layer potential temperature with an MOS (Model Output Statistics) system to produce 50 per cent snow probability values of these parameters appropriate to different locations within the United States of America.

Table 2 - Snow predictors, after Boyden (1964)

Predictor	Mean level of predictor for given snow probability (near sea level)				
	90	70	50	30	10
Height of freezing level above surface (mb)	12	25	35	45	61
Surface temperature (°C)	-0.3	1.2	1.6	2.3	2.9
1000-850 mb thickness (gpm)	1279	1287	1293	1297	1302
1000-850 mb adjusted thickness (gpm)	1281	1290	1293	1298	1303
1000-700 mb thickness (gpm)	2751	2773	2789	2803	2823
1000-500 mb thickness (gpm)	5180	5238	5258	5292	5334

Table 3 - Snow predictors after Lowndes et al. (1974)

Predictor	Mean level of predictor for given snow probabilities (near sea level)				
	90	70	50	30	10
1000-850 mb adjusted thickness (gpm)	1283	1291	1294	1297	1303
Height of dry bulb freezing level (mb)	0	34	43	50	65
Height of wet bulb freezing level (mb)	-8	3	10	18	34
1000-900 mb adjusted thickness (gpm)	835	841	843	845	848

Predictors of conditional probability of snowfall on 31 May 1977

The probabilities in Table 4 below, refer to the conditional probability of precipitation being in the form of snow rather than rain at a particular observation. Therefore, the chances of snow occurring at some time during a whole day, not at a particular time, however, are obviously much higher than the above conditional values. In the preceding analysis of snowfall distribution the lowest elevations at which snow was reported probably corresponded to probability levels of ten per cent or below.

Table 4 - Values of predictors on 31 May 1977 and predicted level of snowfall probability.

Predictor	Predictor value at Melbourne, 31 May 1977	% Probability at sea level i.e. Melbourne	50% level altitude	10% level altitude
Height of freezing level (dry bulb) above ground (mb)	90 mb	10%	440 m	232 m
1000-850 thickness (gpm)	1300.5 gpm	10%		
1000-850 mb adjusted thickness (gpm)	1301.8 gpm	10%	264 m	near sea level
1000-700 mb thickness (gpm)	2800 gpm	30%		
1000-500 mb thickness (gpm)	5240 gpm	60%	near sea level	
Above Predictors after Boyden (1964)		Below Predictors after Lowndes et al. (1974)		
Height of dry bulb freezing level (mb)	90 mb	10%	376 m	200 m
Height of wet bulb freezing level above ground (mb)	54 mb	10%	352 m	160 m
1000-900 mb adjusted thickness (gpm)	850 gpm	10%	322 m	92 m

In order to compare the predicted levels in Table 4, conditional probabilities need to be estimated for 31 May. These were derived by analysing the 9.00 am and 3.00 pm synoptic observations. Only cases where precipitation was occurring were examined. (See Table 5)

Table 5 - Percentage of precipitation reported as snow against elevation ranges (from 0900 and 1500 EST synoptic observations) Victoria, 31 May 1977

Station altitude range (above sea level)	Form of precipitation (No.of cases)		
	Snow	Rainfall	% cases snow
0-150 m	2	21	9
150-300 m	3	8	27
300-600 m	5	1	83
600-900 m	4	-	100
900 m	1	-	100

To obtain approximate levels corresponding to those examined in Table 4, the above percentages were plotted against their altitude range midpoints (Figure 18). Figure 18 indicates a 50 per cent level at an elevation of near 320 metres, a 10 per cent level near an elevation of 75 m and a probability near sea level, e.g. Melbourne, of less than ten per cent. Although the number of observations used to obtain the above values are small, the values compare well with those predicted in Table 4, excepting those predicted by the 1000-500 mb and 1000-700 mb thickness methods. These two methods strongly overpredict the likelihood of snow at low levels in this case study.

Glahn and Bocchiere (1975) predictors in relation to this cold outbreak

Glahn and Bocchiere (1975) found that there were large variations in 50 per cent snow probability 1000-500 mb thickness values across the United States of America notwithstanding altitude considerations. West coast values are around 518 dm whereas on the east coast the USA values are near 534 dm. This difference is due to characteristically different temperature traces: generally temperture traces corresponding to the west coast are more unstable. From synoptic considerations southeastern Australia should experience air mass conditions more like the west coast of the USA than the east coast where arctic, continental type air masses are experienced. Therefore, thickness may need to be as low as 518 dm over Melbourne before the 50 per cent level of snow probability is reached. In this cold outbreak the 1000-500 mb thickness value of 524 dm seems to correspond to a probability of less than ten per cent at sea level (see above). This confirms the idea that the west coast of the USA may have similar thickness values as snow predictors. The 850 mb temperatures derived by Glahn and Bocchiere (1975) also show a marked difference between the east and west coasts of the USA. A 50 per cent level on the west coast corresponds to about -7 or -8°C whereas on the east coast it is about -2 or -3°C. Again

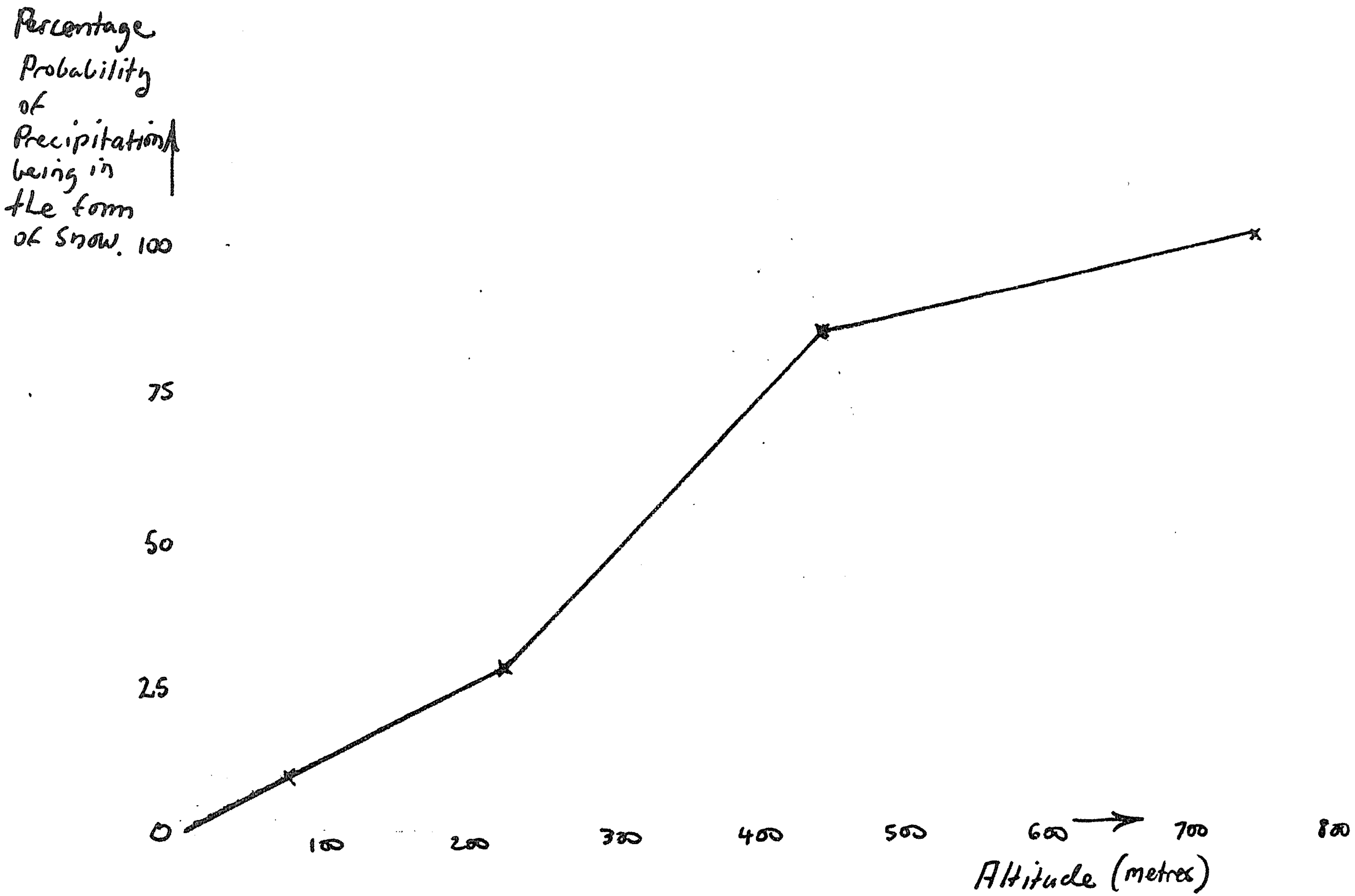

Fig 18. Relation between probability of precipitation being in

Fig 19. Reports of Snowfall - Victoria, 31 May 1977

the 850 mb temperature on 31 May 1977 of -4°C confirms the similarity of the US west coast to southeastern Australia. The local differences in thickness values and 850 mb temperatures when used as predictors make it clear that an analysis should be carried out to establish appropriate parameters for Australia. Note: the only other work that touches on this problem in Australia is by Noar (1970) where he relates 1000-500 mb thickness values to freezing levels by assuming a saturated adiabat-type trace.

Other predictors

(a) Lumb (1961, 1963) in his work on downdrought penetration of snowfall below the wet bulb freezing level, suggested that snow was unlikely to fall below the 3.5°C wet bulb level but could be expected to fall to the 1.5°C wet bulb level. Applying this to 31 May indicates that snow was likely to fall to about 217 m above sea level, snow at sea level would be possible but unlikely.

(b) Working rules in the Australian region - Lamond (1967) proposed a rough rule of -15°C at 700 mb and -30°C at 500 mb and this is satisfied in this situation. Therefore, widespread heavy snow is predicted. Actual values were -15°C at 700 mb and -35°C at 500 mb. A working rule in the Victorian Regional Office is to take an elevation 500 m below the dry bulb freezing level as the cut-off for snow falls. This gives a cut-off altitude in this case study of 360 m.

As in Table 1, many stations in southern Victoria of 175 to 200 m elevation reported snowfalls and isolated falls were reported to near sea level. Thus Lumb's rule works quite well. However, the working rule of 500 m appears less successful, possibly because it ignores dew-points.

SOME OTHER SEVERE COLD OUTBREAKS

It is of interest to compare this event (31 May 1977) with some other severe cold outbreaks. Some occurring before 1943 (when radiosonde data were first collected on a regular basis) are listed in the following table:

Table 6 - Some severe cold outbreaks before 1943 in Melbourne

Date Melbourne Max/Min Temperature	General Wind Direction	9 am Dew-point	Pressure Tendency (9am-9pm)	Phenomena reported in Melbourne Observation Journal (plus other accounts)
31 August 1849	Before synoptic records for Melbourne began the streets of Melbourne were reported covered in several inches of snow.*			
9 August 1872 6.7°C/3.3°C	W/NW	2.4°C	+ ve	Coldest August day on record. Rain and hail.
12 May 1896 8.3°C/5.5°C	-	5°C	+ ve	Equal coldest May day on record. Rain.

Date Melbourne Max/Min Temperature	General Wind Direction	9 am Dew-point	Pressure Tendency (9am-9pm)	Phenomena reported in Melbourne Observation Journal (plus other accounts)
15 April 1900 8.9°C/6.8°C	-	3°C	+ ve	Coldest April day on record. Showery.
28 July 1901 7.4°C/0.7°C	-	3°C	+ ve	Rain, lightning, thunder and hail. Snow fell over much of Western and Central Victoria.*
29 October 1922 9.0°C/6.4°C	W/SW	7.0°C	+14.7mb	Coldest October day on record. Rain and wind squalls.

* Victorian Year Book - 1974

Note: Some of the coldest days on record for Melbourne (particularly in June and July) occurred in fog situations. Also situations where rain occurred in a northerly air stream after a cold morning often had very low maximum temperatures. To distinguish cold outbreak situations from these other situations, subjective use of synoptic parameters apart from maximum temperatures needs to be made. Typical features of cold outbreak days are low temperatures, low dew-points, west to southwesterly winds, snowfalls to low levels, a rising barometer, shower activity, hail and thunder. With radiosonde data cold outbreaks should be easily distinguishable from other very cold days. Table 7 shows 1000-500 mb thickness values, 900 mb temperatures and 850 mb temperatures for severe cold outbreaks since 1943.

CONCLUSION

A severe cold outbreak occurred over Victoria on 31 May 1977 producing widespread snowfalls to low levels. On the synoptic scale this event appears to be the result of an energy dispersion process.

A reasonably good picture of the snowfall distribution and intensity on 31 May 1977 was obtained by combining various data sources. A significant precipitation shadow effect was evident in eastern parts of the State. This type of rainshadow is evident in seasonal averages. This would be expected as westerly flow predominates over Victoria over the year. Exceptionally heavy snowfalls were evident in the Latrobe Valley, in comparison with other areas of a similar elevation.

Various snowfall predictors were tested on this situation. The coarse predictors of snowfall such as the 1000-500 mb thickness did not work well. The work of Glahn and Bocchiere (1975) indicates that work needs to be done to identify the values of these parameters appropriate to Australia. The parameters more closely related to lower levels, namely dry and wet bulb freezing levels and the 1000-900 mb adjusted thickness correspond well in their predictions with the observed field. The working rule used in the Victorian Regional Office of snow falling to 500 m below the dry bulb freezing level gave poor results.

Other cold outbreaks are tabulated to provide a record, and are compared with the 31 May 1977 situation.

Table 7 : Some severe cold outbreaks since and including 1943 - in Melbourne

Date Melbourne max. min Temperatures	General wind direction	9 am dew-point	Pressure Tendency (9 am - 9 pm)	Phenomena reported in Melbourne Observation Journal (plus other accounts	1000-500 mb thickness	850 mb temperature	900 mb temperature
19 July 1951 6.7°C/2.9°C	S/SW	4.3°C	+3.6 mb	Snow, very light in many of northern and eastern suburbs during the morning. Rain.	527 dm 0730 GMT	-4.0°C 0730 GMT	-0.8°C
20 July 1951 7.7°C/1.4°C	W/SW	2.3°C	+2.9 mb	Very light snow and a heavy hail shower at 5.45 am. Some snow flakes in the city during the morning. Showers.	526 dm 0730 GMT	-5.4°C 0730 GMT	-2.2°C
15 July 1966 9.2°C/3.9°C	SW/SE	3.8°C	+3.8 mb	Frequent showers, hail. *Large area of low country in NE Victoria was covered by snow, including Wodonga and Wangaratta. Snow also fell in the Latrobe Valley.	525 dm 2310 GMT 14th	-3.2°C 2310 GMT 14th	-1.9°C
4 August 1943 9.7°C/2.9°C	W/SW	1.7°C	+8.3 mb	Hail and rain showers. *Snow fell over an area from the Western District well into NSW. Snow fell for the first time in 20 years at Sale.	(prior to records)		
31 August 1945 10.4°C/2.8°C	W/SW	1.1°C	+6.6 mb	Light showers, hail. *Snow fell on the coast at Hastings and at Port Campbell.	532 dm 1430 GMT	-4.5°C 1430 GMT	-0.4°C

Date Melbourne max. min Temperatures	General wind direction	9 am dew-point	Pressure Tendency (9 am - 9 pm)	Phenomena reported in Melbourne Observation Journal (plus other accounts	1000-500 mb thickness	850 mb temperature	900 mb temperature
9 August 1951 7.7°C/1.9°C	W/SW	1.3°C	+3.7 mb	Four showers in city accompanied by light flakes of snow. *Two inches of snow fell in some Melbourne suburbs and falls extended to sea level over the Mornington Peninsula and Gippsland. (Also see Shanahan 1979).	Not available	-5.4°C 0730 GMT	-0.9°C
11 September 1969 8.3°C/3.9°C	W/SW	1.7°C	+5.2 mb	Showery. Snow showers reported in the city between noon and 3 pm. Snow was also reported from many suburbs.	527 dm 2300 GMT 10th	-3.7°C 2300 GMT 10th	-0.6°C

*Victorian Yearbook - 1974

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