Climatology of cold outbreaks with snow over Tasmania

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Selected Hobart upper-air data, surface observations from several sites in Tasmania and reports of cold outbreaks in Bureau of Meteorology publications are studied to produce a climatology of cold outbreaks with snow over Tasmania. This climatology is used to develop an objective definition of a cold outbreak that can be applied to Tasmanian weather conditions for the purposes of climatology, forecasting and classification of extreme weather. The parameters 1000-500 hPa thickness, 500 hPa temperature, freezing level and 850 hPa temperature, which are readily measured and are available from numerical model output, can be used to differentiate between air masses associated with cold outbreaks producing snow and those relating to less extreme weather. It is found that over the thirty years from 1962 to 1991 the frequency of cold outbreaks with snow over Tasmania declined by more than 60 per cent. There may be a link between this decline and climatic change in the region as revealed by studies of ocean temperatures, air temperatures and long-term variability of Tasmanian rainfall.

Introduction

Tasmania is an island of area 63 300 square kilometres, with a central plateau containing peaks to about 1500 metres above sea level (Fig. 1). Oceans that are meteorologically data-sparse border it to the west and south, and these are the directions from which all cold fronts come. To the west the closest meteorological station is at Kerguelen Island, 5700 kilometres away, and to the south the closest is Dumont d'Urville in Antarctica, 2700 kilometres away (Fig. 2). Remote sensing, occasional observations from ships and drifting buoys, and numerical weather prediction models provide the only description of the behaviour of synoptic systems approaching Tasmania from the west or south. A Geostationary Meteorological Satellite infrared image of a cold outbreak approaching south-eastern Australia is given in Fig. 2.

It is of interest to meteorologists and the local community to have an appreciation of the nature and frequency of periods of cold weather in Tasmania. There is particular interest in snowfall because in some years no appreciable snow settles, whereas in other years a substantial depth of snow lies on the highlands for several months. Climatic fluctuations may be expected to affect the altitude to which snow settles over Tasmania. Occasionally snow falls to low altitudes and disrupts daily life. Falls settling to about 600 metres above sea level cause some highway closures and isolation of small highland settlements. Falls to 450 metres cause closures of more major highways, isolation of several towns and disruption of their local services. Significant falls to sea level over the major cities have occurred only rarely but are accompanied by considerable cost and social chaos.

The term ‘cold outbreak’ is used loosely in Australia and elsewhere to indicate a sudden onset of unusually cold weather. In Tasmania it is most often used in conjunction with unusually heavy snowfall. Invariably the snowfall is associated with the passage of cold fronts within a large amplitude trough in the middle tropospheric circulation and occurs in the pre-frontal and/or post-frontal air mass.

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Fig. 1 Tasmanian topography and place names.

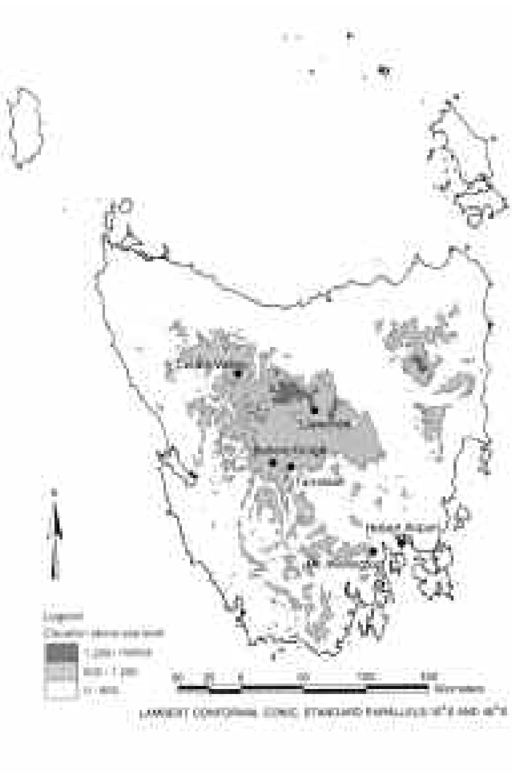


Fig. 2 A cold outbreak approaching southeastern Australia, June 1995.

Several studies of Antarctic mid-latitude interactions, and cold outbreaks in particular, have been undertaken with a view to further understanding the climate of southern Australia (e.g. Karelsky 1954; Maher 1955; Morley 1957; Hannay 1959; Noar 1970; Taylor and Stern 1982; and Perrin and Simmonds 1995). Case studies by Karelsky (1954) suggest that, in the Tasmanian region, a significant amplification of a mid-atmospheric short wave trough in the vicinity of Tasmania will be necessary for a 'cold outbreak' in any season but winter. During winter, sufficiently cold air can be advected over Tasmania from about 25 degrees longitude further west without being modified much by the ocean over which it passes. In this season, therefore, a trough amplification occurring further west can produce a 'cold outbreak'. Huschke (1959) defines a 'cold-air outbreak' as the movement of cold air from its source region, almost invariably applied to a vigorous equatorward thrust of cold polar air or a rapid equatorward movement of the polar front. This approach is similar to that of Karelsky. Hannay (1959) defines a 'cold outbreak' as a set of weather conditions producing a temperature of 0°C or lower at 850 hPa pressure at the southern coastline of (mainland) Australia with a further restriction on 1000-700 hPa thickness. This is clearly inadequate for Tasmania where the mean temperature at 850 hPa is less than 0.5°C for the months of July and August. Perrin and Simmonds (1995) define a 'cold outbreak over Melbourne' as a day on which the maximum temperature is more than two standard deviations below the long-term mean for that month. Hence a summertime cold outbreak will usually be warmer than a wintertime cold outbreak. The definition includes cold days associated with slow moving high-pressure systems as well as days immediately following fronts. This is a departure from the common concept given above and does not require a sudden onset.

Two case studies presented in internal reports of the Bureau of Meteorology illustrate different synoptic developments and patterns of precipitation that can be associated with cold outbreaks with snow settling below 200 metres above sea level in Tasmania. These are summarised below.

On 24 and 25 July 1986 widespread snowfalls occurred across Tasmania and the southeastern Australian mainland (Elliott 1989). Snowfalls in Tasmania descended to sea level over most of the coastal area, although the central north and northeast remained generally free of precipitation, reflecting the rain shadow effect of the central plateau and the northeast highlands. The distribution of rainfall and melted snow for the 24 hours to 9am 25 July is shown in Fig. 3. A study of the synoptic sequence revealed that an intrusion of mid-latitude air to Antarctica, resulting in a large amplitude long-wave ridge to the west of Tasmania, was a significant factor in producing a large amplitude tropospheric trough in Tasmanian longitudes. A cold front crossed Tasmania on 24 July and the prevailing wind in the post-frontal stream was almost due southerly. The post-frontal air mass had a long southerly trajectory that could be traced to the Antarctic coast (Perrin and Simmonds

Fig. 3 Rain and melted snow distribution (mm) for the 24 hours to 9am, 25 July 1986.

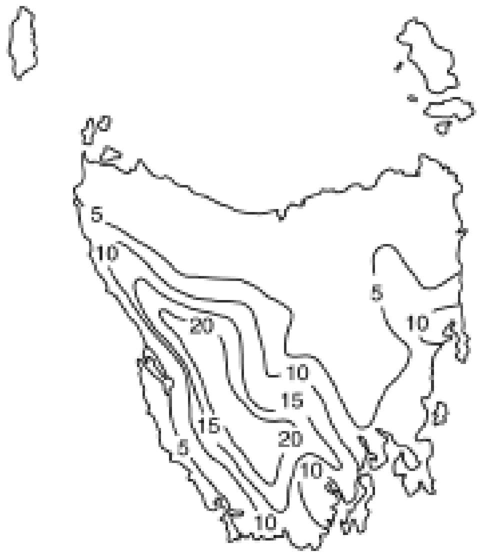


Fig. 4 MSL pressure (solid lines) and 1000-500 hPa thickness (dashed lines), 9am 25 July 1986.

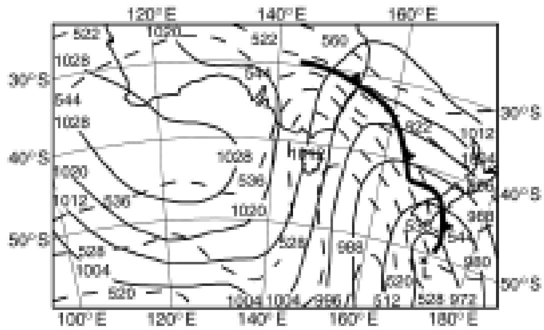
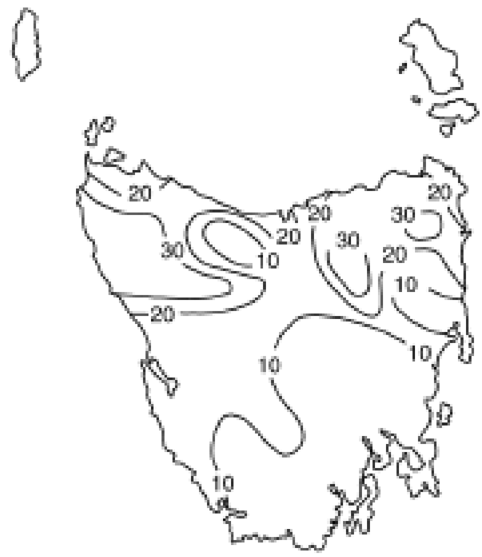


Fig. 5 Rain and melted snow distribution (mm) for the 24 hours to 9am, 28 June 1990.



1995) and snow fell to low altitudes from the very cold unstable post-frontal stream for about 12 hours. The coldest pool of air crossed southern Tasmania on the morning of 25 July. A synoptic chart illustrating the event is shown in Fig. 4.

Some air mass characteristics over Hobart on the morning of 25 July were:

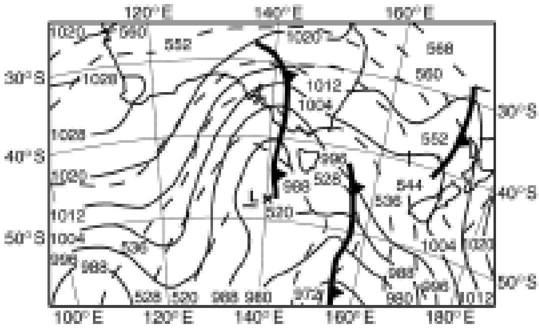
- 850 hPa temperature: -7.6°C;
- Freezing level: 370 m;
- 1000-500 hPa thickness: 522 gpdm;
- 500 hPa temperature: -25.6°C.

On 27 June 1990 unusually heavy snowfall occurred in northern Tasmania (Jones and McCulloch 1992). The heaviest falls were in the central north and northeast highlands, with snow that did not settle being reported at sea level towns along the northwest coast. The distribution of rainfall and melted snow is shown in Fig. 5. A study of the synoptic sequence revealed that a long wave trough west of Tasmania gradually amplified and moved eastward to be positioned near Tasmania on 25 June. Amplification continued for several days. There was no direct Antarctic interaction, the cold air mass being advected over Tasmania from the Great Australian Bight. The heavy snowfalls over the north were produced mostly as prefrontal precipitation through an already very cold lower atmosphere. Snow fell to sea level in the northwest in response to formation of a small low at the surface over northern Tasmania (not shown) which brought cold low level air from the inland highlands to the coast and further cooled the lowest layers of the atmosphere. A synoptic chart showing the situation shortly before the front crossed Tasmania is given in Fig. 6.

Some air mass characteristics over Hobart on the morning of 28 June were:

- 850 hPa temperature: -4.2°C
- Freezing level: n/a
- 1000-500 hPa thickness: 527 gpdm
- 500 hPa temperature: -26.8°C.

Fig. 6 MSL pressure (solid lines) and 1000-500 hPa thickness (dashed lines), 9 am 27 June 1990.



The purpose of this study is to produce a climatology of cold outbreaks over Tasmania using a definition that agrees with the popular perception in published newspaper and Bureau of Meteorology reports and the concepts used by Karelsky and Huschke mentioned above. The presence of snow to low levels may be used to identify some events as 'cold outbreaks', but other weather events in which the lower troposphere is similarly cold are not accompanied by significant snowfall. An objective definition of a cold outbreak that can be used to categorise events for climatological purposes without reliance on snowfall records would be useful. Such a definition is attempted here. Parameters, based on surface and upper air data, that show significant variation with the severity of cold outbreaks as judged from snowfall records are chosen. Categorisation of events based on these parameters provides an alternative, and objective, definition of a cold outbreak. A brief investigation of temporal changes during recent decades in the occurrence of snowfall and cold outbreaks, so defined, follows.

Source material

Records of snowfall, unusual snowfall and abnormally cold conditions in Tasmania were obtained from the Bureau of Meteorology publications *Monthly Climate Bulletin* (some issues missing), *Weather Review Tasmania* and *Monthly Weather Review Tasmania*, which together cover all years from 1957. These publications are considered the most reliable and informative sources of this information as they include a summary of reports from Bureau of Meteorology observing sites as well as information on excessive snowfall obtained through news services. Prior to 1957 there are no records of comparable reliability. In the Tasmanian highlands official reporting stations are few, and no highland station operated for the entire period of the study.

In identifying cold outbreaks of various severities from these records, the following definitions and criteria were used.

A 'cold outbreak with snow' is one that causes disruption to daily life with an associated cost to the community. It requires the Bureau of Meteorology to issue warnings for land areas, probably due to snow, such as alerts for motorists and highland hikers. Severe frost warnings may be necessary after the outbreak. Where the altitude to which snow fell is mentioned in the publications, the threshold chosen for a 'cold outbreak with snow' was 600 metres above sea level, this being the altitude where snowfall begins to make a significant impact on the community such as some highway closures and isolation of small settlements. This altitude is about 1.75 standard deviations below the mean winter freezing level.

A more significant 'cold outbreak with snow' causes the closure of more major highways and isolation of several towns. It occurs when snow settles below 450 metres above sea level, this being close to 2 standard deviations below the mean winter freezing level.

A 'cold outbreak with snow to low levels' is one that produces social chaos, and it occurs when snow settles below 200 metres above sea level, about 2.5 standard deviations below the mean winter freezing level.

A 'non-severe cold outbreak' produces less significant snowfall and necessitates no temperature-related warnings for land areas.

During the period 1957 to 1986 the data showed 283 days with the snowline at 600 metres or lower. Of these, snow settled at or below 450 metres on 184 days. On about eight per cent of the days, mainly in the 1960s, the publication did not specify the snowline, however there was enough information about the impact on the community to indicate it was below 600 metres. In these cases it was assumed to be between 450 and 600 metres.

Upper air data for the 40 years 1957 to 1996 inclusive for Hobart Airport, the only Tasmanian site where radiosondes are released, were obtained from the National Climate Centre, Bureau of Meteorology. This dataset is referred to here as Upperair5796. Soundings were performed twice daily, at 9 am and 9 pm local time, but there was much data missing for 1991. Because the sounding presents an instantaneous view of the atmosphere, the coldest air may have been missed in the case of intense, short wavelength thermal troughs so it is likely that on many occasions the thermal trough peaked with a lower value than that observed. On some occasions the 9 pm data included brief cold bursts which were not evident in the 9 am data. However, long-term monthly average and extreme values of the relevant data show no significant differences between the 9 am and 9 pm datasets.

In order to simplify the analysis, several representative upper air parameters were chosen or derived from the data. The 1000-500 hPa thickness (THK) was chosen as a measure of the relative coldness of the lower troposphere, because it is routinely analysed for forecasting purposes and is able to be estimated fairly accurately via satellite technology. It is also readily obtainable as output from numerical weather prediction models. The 500 hPa temperature (T500), the freezing level (FZL) and the 850 hPa temperature (T850) were also considered. Where a sounding contained multiple freezing levels the lowest one was used. After 1986 the Bureau of Meteorology stored only significant and standard levels from atmospheric soundings so freezing level data were not readily obtainable. The freezing level and 850 hPa temperature have been used with only limited success in solving the more difficult problem of differentiating between snowfall and rainfall, as discussed in detail by a number of authors, including Boyden (1964), Booth (1970), Lowndes et al. (1974) and Heppner (1992). Nevertheless, for the purpose of studying the origin and characteristics of the air mass, rather than the complexities of whether or not significant snow will fall, these parameters are pertinent. The incorporation of the moisture profile of the air mass has been left as a subject for further study, and could be provided by considering moist static energy (Gibson 1996).

Some definitions

In this paper the terms 'winter', 'mean winter value' and 'snow day' have the following meanings: 'Winter' refers to July and August, these two months being associated with the coldest lower troposphere over Hobart Airport, Tasmania.

The 'mean winter value' of a meteorological element refers to the mean taken over July and August. A 'snow day' is a day on which snowfall, which does not necessarily settle, is observed from at least one site in Tasmania.

As noted above, the 1000-500 hPa thickness is denoted by THK, the freezing level by FZL and the 850 hPa and 500 hPa temperatures by T850 and T500.

Analysis and results

From the published reports a set of seven different weather categories relating to cold outbreaks was constructed. For the 30 years 1957 to 1986 the upper-air data was matched against these categories. Basic statistical analyses were performed on this combined dataset to derive mean values of several upper air parameters for each weather category. These were used to define an alternative categorisation of cold events, based on upper air parameters, corresponding approximately with the definition of a cold outbreak using the occurrence of snow and other weather elements. The upper air and other published data from 1957 to 1996 were used to identify trends in snowfall and chosen upper air parameters over a 40-year period.

Climatology of cold outbreaks

A dataset containing selected upper air and surface parameters, together with a weather category for cold days, for the 30-year period from 1957 to 1986, was constructed as follows. A set of cold days, being those on which FZL and/or THK were below the winter mean (FZL below or at 1500 metres and/or THK below or equal to 538 gpdm), was extracted from the data of 9 am upper air soundings for these years. This set contained about 32 per cent of days in the period. A weather category was assigned to each of these days, using the seven weather categories given below. Surface observations for several sites around Tasmania were also compiled for each day. The dataset comprising the upper air and surface observations and the weather category was used to develop a climatology of cold outbreaks. The resulting dataset is referred to here as Colddays5786. Although it was derived purely using upper air parameters FZL and THK, it contains all Tasmanian snow days and unusually cold days for the given period noted in relevant Bureau of Meteorology publications.

The weather categories used in the dataset are:

1. Not particularly cold or noteworthy: These are the 60 per cent of days in Colddays5786 which are not recorded in the Bureau of Meteorology publications referred to as being notably cold.
2. Very cold without snow: This one per cent of Colddays5786 included several references to severe frost, broken water pipes due to freezing and to very cold periods with no further detail. Some were associated with cold high pressure systems stationed over Tasmania but some involved frontal passages. The number of such days in the dataset is too small to provide meaningful statistical results.

3. Marginal cold outbreak: Snowfall occurred on all these days but the published information was not precise enough to determine whether or not the snowline fell to 600 metres.
4. Some light to moderate snowfall: The snowfall reported on these days indicated a snowline above 600 metres.

5(a). Cold outbreak with snow: These were extracted from the publications in accordance with the definition given earlier, i.e. the threshold altitude for snow settling is 600 metres above sea level.

5(b). Cold outbreak with snow to 450 m or lower: a more significant 'cold outbreak with snow' occurs when snow settles below 450 metres above sea level.

5(c). Cold outbreak with snow to low levels: As for 5(a) and 5(b) but with snow settling to 200 m or lower.

The dataset was examined to find surface and upper air parameters that display a systematic variation with weather category. The percentile range of maximum temperature at sites on Tasmania's post-frontal windward coast and rainfall totals for each frontal passage were not found to be useful in classifying the events. THK, T500, T850 and FZL, all measured at 9 am, do differ systematically with weather category, however. Table 1 shows the percentage of dataset Colddays5786 that corresponds to the weather categories along with the means and standard deviations of the chosen upper air parameters for each category. Thirty-year normals and standard deviations are also calculated for the winter months and for all months. There were many occasions when no cold outbreak was recorded in the publications but at least one of T850, FZL, THK and T500 fell below the averages given in line 5 (Cold outbreaks with snow) of Table 1. Only 19, 25, 33, and 18 per cent, respectively, of occurrences of the single variable below average values in line 5 of Table 1 were associated with recorded cold outbreaks. Of the days on which cold outbreaks were recorded T850, FZL, THK and T500 were below those averages on about 50 per cent.

The Cold Outbreak with Snow subset of Colddays5786 was then further subdivided such that where THK remained at or below 536 gpdm (the average THK calculated in Table 1 for days with some snowfall) for a number of days in association with a cold outbreak, each such period was called one 'cold spell'. Table 2 shows that cold spells are most frequent in winter and early spring.

Table 1. Means and standard deviations of upper air elements for the stated weather category.

	%days	*T850 (°C)*		*FZL (m)*		*THK (gpdm)*		*T500 (°C)*	
		mean	*s.d.*	*mean*	*s.d.*	*mean*	*s.d.*	*mean*	*s.d.*
1. Not noteworthy nor particularly cold	60	-0.9	1.8	1270	220	540	5.0	-24	3.9
2. Very cold without snow	1	-1.9	2.5	1030	350	536	5.7	-26	4.2
3. Marginal cold outbreak	2	-1.8	1.8	1130	210	536	5.6	-26	4.3
4. Some light to moderate snowfall	22	-1.8	1.9	1130	230	536	4.7	-26	3.8
5. Cold outbreaks with snow	9	-3.0	2.2	950	280	532	5.5	-28	4.0
Unclassified (insufficient data)	6								
Full dataset of cold days	100	-1.3	2.0	1200	250	538	5.6	-25	4.1
30-year normal over July and August	-	0.3	2.8	1490	510	539	5.3	-25	3.5
30-year normal over all months	-	3.6	5.0	2200	940	547	9.4	-20	5.2

Table 2. Monthly frequency distribution for cold spells of stated duration (with percentages in parentheses).

Duration of Cold spell (days)	*Total*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
1	69(45)	0(0)	0(0)	1(1)	5(3)	5(3)	7(5)	11(7)	11(7)	17(12)	10(6)	2(1)	0(0)
2-3	73(48)	0(0)	0(0)	0(0)	1(1)	7(5)	11(7)	19(12)	16(10)	12(8)	4(3)	3(2)	0(0)
4-7	10(7)	0(0)	0(0)	0(0)	0(0)	0(0)	2(1)	4(3)	2(1)	1(1)	1(1)	0(0)	0(0)
Total	152(100)	0(0)	0(0)	1(1)	6(4)	12(8)	20(13)	34(22)	29(18)	30(21)	15(10)	5(3)	0(0)

Table 3. Frequency of cold spells having upper air parameters below the averages given in line 5 of Table 1 for cold outbreak days (percentages in parentheses).

snowline(m)	*no. of events*	*T850 (°C)*	*FZL (m)*	*THK (gpdm)*	*T500 (°C)*
0-450	92	3(79)	74(80)	72(78)	62(67)
0-600	152	103(68)	106(70)	103(68)	100(66)

Average values give 5.3 cold spells per year with snow settling to 600 metres altitude or lower. Of these, snow settled below 450 metres about 3.2 times per year, and below 200 metres above sea level about 1.5 times per year. A study of percentile ranges of the upper-air parameters associated with each cold spell showed that the value of each of T850, T500, FZL and THK fell below their means shown in line 5 of Table 1 during about 65 per cent of events. When snow settled to 450 metres or lower, the values for T850, FZL and THK fell below their means shown in line 5 of Table 1 during about 80 per cent of events, and for T500 during about 65 per cent of events (Table 3).

For each cold spell the day with the lowest THK was used to determine the mean conditions of T500 and THK on the coldest day. The day with lowest FZL was used to determine the mean conditions of T850 and FZL on the coldest day. The results of this analysis are given in Tables 4 to 7 which show the average values of the four upper air parameters for various

Table 4. Average minimum parameter values and standard deviations for cold spells with snow settling below 600 metres altitude.

Duration	*T850 (°C)*		*FZL (m)*		*THK (gpdm)*		*T500 (°C)*	
(days)	*mean*	*s.d.*	*mean*	*s.d.*	*mean*	*s.d.*	*mean*	*s.d.*
1	-3.2	2.4	930	280	531	5	-29	3
2-3	-4.1	1.9	800	220	528	4	-30	4
4-7	-4.8	1.7	710	150	526	4	-32	2
Total	-3.8	2.4	850	290	529	5	-30	4

Table 5. Average minimum parameter values and standard deviations for cold spells with snow settling below 450 metres altitude.

Duration	*T850 (°C)*		*FZL (m)*		*THK (gpdm)*		*T500 (°C)*	
(days)	*mean*	*s.d.*	*mean*	*s.d.*	*mean*	*s.d.*	*mean*	*s.d.*
1	-4.0	2.1	830	240	528	5	-30	3
2-3	-4.6	2.0	760	240	528	5	-30	4
4-7	-4.9	1.7	710	140	526	4	-33	2
Total	-4.4	2.1	780	260	528	5	-30	4

Table 6. Frequency distribution of snowline in the given altitude range for cold spells of stated duration (percentages in parentheses).

			Snowline (m)		
Duration (days)	*0-50*	*51-200*	*201-450*	*451-600*	*Total*
1	11(8)	4(2)	22(15)	32(20)	69(45)
2-3	14(9)	9(6)	23(16)	27(17)	73(48)
4-7	2(1)	5(4)	2(1)	1(1)	10(7)
Total	27(18)	18(12)	47(32)	60(38)	152(100)

Table 7. Average values of upper air parameters for given snowlines, along with the number of standard deviations below the mean winter values.

Height of Snowline (m)	Deviation of snowline from mean winter FZL s.d.	T850 (°C) value	T850 (°C) s.d.	FZL (m) value	FZL (m) s.d.	THK (gpdm) value	THK (gpdm) s.d.	T500 (°C) value	T500 (°C) s.d.
0-200	2.5-3.0	-4.8	1.8	710	1.5	526	2.5	-32	2.0
201-450	2.0-2.4	-4.0	1.5	860	1.2	529	2.0	-29	1.0
451-600	1.7-1.9	-2.8	1.1	960	1.0	529	2.0	-29	1.0
601-1500	0-1.7	-1.8	0.7	1130	0.3	536	0.6	-26	0.3

cold spell durations, the frequency of snowline altitude for these durations and mean values of the upper air parameters for the snowline altitude categories. They show that, on average, the altitude to which snow settles decreases with the duration of the cold spell as well as with decreasing tropospheric temperature. For example, in the case of snow below 600 metres, the mean T850 for one-day duration cold spells was -3.2°C compared with -4.8°C for the 4 to 7-day duration events (Tables 4 and 5). For cold spells with snowline below 450 metres this feature is not so marked but overall T850, FZL and THK are lower than for the higher snowline. It is significant that of cold spells with duration 4 to 7 days, only one had a reported snowline above 450 metres.

A closer look at the snowline in conjunction with duration of the cold spell and the upper air parameters indicates that cold spells usually last 1 to 3 days and more than 60 per cent produce snow settling below 450 metres altitude (Table 6). It is well known that during prolonged snowfall the freezing level decreases; statistics on the altitude of snowline for different cold-spell durations shown in Table 6 support this, with snow to lower levels being relatively more frequent among the cold spells lasting more than one day.

Table 7 gives the mean value of the upper air parameters for cold spells associated with the various snowlines and also includes the number of standard deviations below the winter mean. A colder atmosphere coincides with snow to 200 metres altitude or lower, but for a snowline between 200 metres and 600 metres the major difference lies in FZL and T850.

The results in this Table may be used to produce an alternative, and objective, definition, allowing weather events to be divided into categories which correspond approximately with ‘cold outbreak’, ‘cold outbreak with snow’ (snowline 600 m or lower) and ‘cold outbreak with snow to low levels’ (snowline 200 m or lower). In this alternative definition, these weather categories are defined as follows.

A ‘cold outbreak’ is defined as the passage of a cold front where the post- frontal air mass has the following properties:

- mean 1000-500 hPa thickness of 2 standard deviations (10 gpdm) below the winter mean of 539 gpdm;
- mean 850 hPa temperature at least 1.1 standard deviations (3°C) below the winter mean of 0.3°C;
- 500 hPa temperature at least 1 standard deviation (3.5°C) below the winter mean of -25°C; and
- freezing level at least 1 standard deviation (510 m) below the winter mean of 1490 m.

A ‘cold outbreak with snow’ has the additional criterion that snowfall settles to 600 m or lower which is near 1.7 standard deviations (870 m) below the mean winter freezing level (1490 m).

A ‘cold outbreak with snow to low levels’ is defined as the passage of a cold front where the post-frontal air mass has the following properties:

- 1000-500 hPa thickness at least 2.5 standard deviations (13 gpdm) below the winter mean value of 539 gpdm,
- 500 hPa temperature at least 2 standard deviations (7°C) below the winter mean of -25°C,
- 850 hPa temperature at least 1.8 standard deviations (5°C) below the winter mean of 0.3°C,
- freezing level at least 1.5 standard deviations (770 m) below the winter mean of 1490 m, and
- snowfall settles to 200 m or lower, which is near 2.5 standard deviations (1280 m) below the mean winter freezing level of 1490 m.

The 45 recorded cold spells with snow to 200 metres or lower satisfy the upper air criteria (based on the Hobart Airport soundings) for a ‘cold outbreak’ on more than 80 per cent of occasions when each upper air parameter is considered separately, and those for a ‘cold outbreak with snow to low levels’ on 50 - 70 per cent of occasions. The 107 recorded cold spells with snow between 200 metres and 600 metres satisfy each of the upper air criteria for a ‘cold outbreak’, considered separately, on about 40 - 60 per cent of occasions, and for a ‘cold outbreak with snow to low levels' on 30 per cent of occasions for T850 and about 20 per cent of occasions for FZL, THK and T500. Twelve per cent of the 152 recorded cold spells satisfied none of the upper air requirements of the above definition, and 18 per cent of the 45 recorded cold spells with snow below 200 metres satisfied none of the upper air requirements for the definition of a cold outbreak with snow to low levels.

As mentioned earlier, there are many occurrences of low values of the upper air parameters that did not result in cold outbreaks being recorded in the publications.

Frequency of snow days and cold tropospheric parameters

According to the publications, snowfall, which did not necessarily settle, was reported on about 11 per cent of days in the 40 years 1957 to 1996. Published data were incomplete for some early years. Due to this, and the few observing sites in the Tasmanian mountains, it is likely that snow settled on the ground somewhere in Tasmania more frequently. Nevertheless, the results provide minimum annual occurrences of significant snowfall and minimum monthly frequency distributions. The average annual snow day frequency for five-year periods from 1962 to 1996 is shown in Fig. 7, and the average monthly snow day frequency for the whole period studied (1957 to 1996) is shown in Fig. 8. Snowfall occurs in all months but with a marked maximum during July to September. The number of snow days declined during the 1970s and 1980s, then increased again in the early 1990s. This trend shows in individual station records as well as those given in the publications for the state as a whole, even though the results in Fig. 7 are undoubtedly affected by the short-term operation of the few stations above 900 metres altitude. The dates of operation of the high altitude stations are given in the Appendix. Annual average occurrences of snow settling to below 600 metres and to below 450 metres also declined during the 30-year period from the early 1960s, the decline being most marked after the early 1980s as shown in Fig. 9, which gives the annual frequency of days with snow reported below these levels averaged over five year intervals.

During the period 1992 to 1996 the occurrence of snow to or below 600 metres remained low but Tasmanian snow days increased. A monthly distribution of cold outbreaks with snow, as defined by snow settling to 600 metres or lower, shows no significant difference, in terms of relative frequencies, between years with heavier or lighter snowfall.

Following the procedure, discussed earlier, of using upper air parameters to define an objective categorisation corresponding approximately to cold outbreaks with snow, a similar procedure was followed to define a categorisation of cold outbreaks based on upper air parameters. The average values of THK, T500, FZL and T850 shown in Table 5 for all cold-spell durations (i.e. the row 'Total') were used as a threshold to obtain the annual average number of days in Upperair5796 with at least one of these parameters falling to or below the chosen threshold. The resulting variation of the frequency of cold outbreaks (so defined) is given in Fig. 10 which shows five-year

Fig. 7 **Five-year average annual snow day frequency 1957 to 1996.**

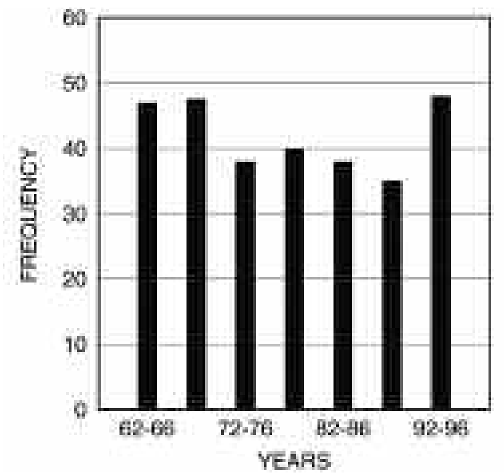


Fig. 8 **Average monthly snow day frequency 1957 to 1996.**

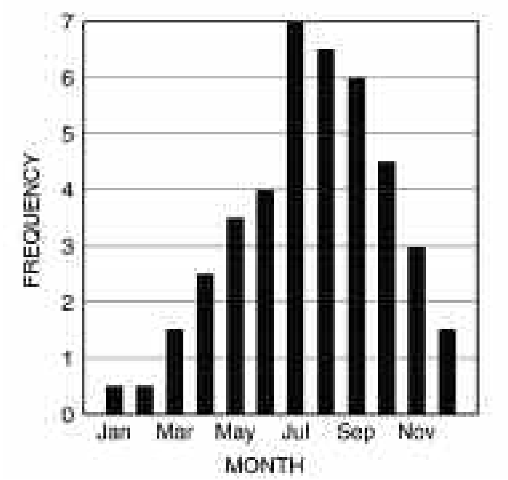
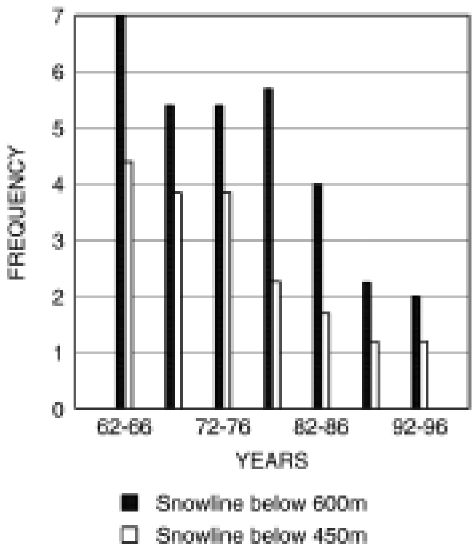


Fig. 9 Five-year average annual frequency of stated snowlines 1962 to 1996.



annual average occurrences of days with low values of THK (<528 gpdm), FZL (<780 m), T850 (<-4.4°C) and T500 (<-30°C). Because some snow data in early years were missing from the publications, the trends in Figs 6 and 8 commence in 1962. Figure 10 contains no freezing level data after 1986 and no data for 1991 due to lack of records. The trends in the parameters T500, T850 and THK indicate that a cold lower troposphere over Tasmania became less frequent from the mid 1960s to 1990 but became more frequent during the period 1992 to 1996.

Discussion

The statistics provided in Tables 1 to 7 provide guidance in forecasting snow in Tasmania. The statistics on the altitude of the snowline and corresponding upper air parameters may be compared with forecasting rules produced for other locations. For example, The UK Meteorological Office Forecasters' Reference advises that snow is not expected to settle if the surface air temperature is 4°C or more (The Meteorological Office, 1993). A simple rule based on a saturated lapse rate of 0.75°C per 100 metres suggests precipitation will fall as snow to about 300 metres below the freezing level. It provides the following thresholds for a 50 per cent probability of snow to sea level: surface temperature 1.6°C, or FZL 350 metres, or THK 526 gpdm. Another rule, based on an International Civil Aviation Organization standard atmosphere, suggests precipitation will fall as snow to sea level when THK is 524 gpdm or lower, and to 600 metres when THK is at most 533 gpdm. Table 7 gives results suited to Tasmanian conditions that are broadly in line with these rules. These include:

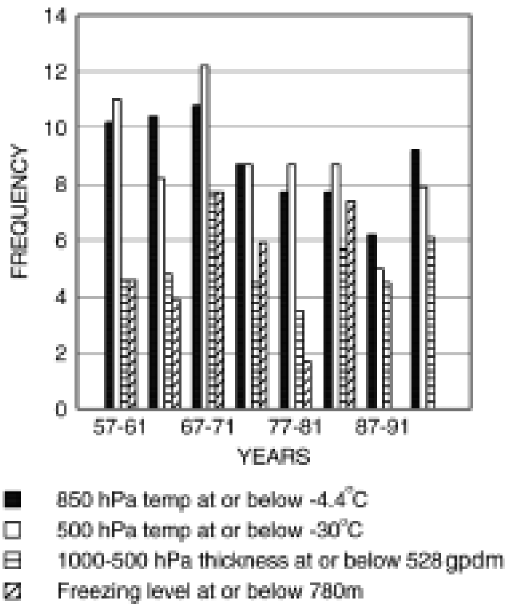
- snow may be expected to about 500 m below the freezing level;
- highland snowfall is associated with a thickness of 536 gpdm or lower and 850 hPa temperature below -2°C;
- snow affecting major roads is associated with a thickness of 529 gpdm or lower, and it may fall on lowland areas when thickness is 526 gpdm or lower; and
- 500 hPa temperature of -30°C is likely to be associated with significant snowfall.

The failure of maximum temperatures and rainfall totals to identify cold outbreaks may be explained by the existence of other influences on these elements. The quantity of precipitation varies considerably with frontal passages whatever the temperature contrast across them. The maximum temperature over 24 hours may occur before or after a front. Cloudiness, precipitation, radiational cooling, turbulence and adiabatic effects, such as the foehn effect, also affect the temperature. Most of these deficiencies would apply to the use of high altitude as well as sea-level maximum temperature and rainfall figures. The quantity of precipitation and ambient temperatures also influence the altitude of the snowline.

As noted earlier, 12 per cent of the reported cold outbreaks with snow did not satisfy any of the derived upper air criteria for a cold outbreak. This may be due to Hobart Airport upper air data not representing Tasmania as a whole accurately. It has also been noted that application of the derived upper air criteria to the full set of upper air data highlights a large number of low values of the upper air parameters that do not coincide with records of snowfall to low levels. In general some snowfall was reported with these. It is reasonable to suppose that where moisture profiles are such that snow does not settle to low levels, these cold air masses pass largely unremarked. These events are defined as the 'non-severe cold outbreaks'. Further study to include moisture profiles will be needed in order to delineate objectively, using upper air parameters, 'cold outbreaks with snow' (i.e. those with snow below 600 m) from 'non-severe cold outbreaks' (i.e. those with less significant snowfall).

The variation over the period studied in the frequency of snowfall and of cold outbreaks as defined using the upper air parameters studied is possibly affected by the changes in high altitude observing sta-

Fig. 10 Five-year average annual frequency of stated upper air parameter values 1957 to 1996 (except 4 years 1987 to 1990).



tions and radiosonde technology over the period. Nevertheless, the variations are in accord with studies of rainfall and temperature variations in Tasmania. The short period of operation of most of the high altitude Tasmanian weather observing stations was noted earlier. Over the study period there have been many changes to radiosonde technology (Gaffen 1993). Hurrell and Trenberth (1998) showed that the changes made over the Australian network between 1987 and 1989 resulted in an artificial warming of tropospheric temperatures of less than 0.5°C. However, Parker et al (1997) suggested that a real lower tropospheric warming of about 0.3°C occurred between the periods 1965-74 and 1987-96 for the zonal band around 40°S.

A study of rainfall variability over Tasmania, taken over an 80-year period to 1991 (Shepherd 1995), shows a decreasing trend in Tasmanian rainfall, which cannot be distinguished from natural long-term variability. An Australia-wide study (Nicholls et al. 1997) shows a reduction in Tasmanian rainfall from the mid 1970s to 1992 during which period the frequency of Tasmanian snowfall to 450 metres or lower declined as did the frequency of cold values of the upper air parameters. The reduced frequency of snowlines below 600 metres occurred from the early 1980s.

A general increase in maximum temperatures is apparent in the observations from one meteorological station in Tasmania's highlands, Butlers Gorge (Fig. 1), which has records extending from 1957 to 1991. A study of high quality surface air temperature records throughout Tasmania (Shepherd, personal communication) shows an increase of about 1.5°C in annual mean maximum and 1.3°C in annual mean minimum over the 40 years to 1990. Jones (1999) shows an average increase of about 1°C in maximum and about 0.7°C in minimum in southeast Australian surface air temperatures from 1950 to 1994 (his Figs 6(e) and 8(e)). Jones and Trewin (2000) analyse the spatial structure of these temperature changes. A study of the southwest Pacific Ocean between longitudes 141°E and 179°E and latitudes 39°S and 49°S, which surrounds Tasmania, (Holbrook and Bindoff 1997) indicate that ocean temperatures to a depth of 100 metres warmed by 0.13°C during the 34 years to 1988.

Collins and Della-Marta (1999) suggest that temperatures over southeastern Australia were generally higher in the late 1980s than in the mid 1990s. During 1992 to 1996 Tasmania experienced an increase in cold occurrences in the lower troposphere and an increase in snow days, however occurrences of snow settling to 600 metres or lower did not increase.

Gibson (1992) investigates a poleward trend from 1976 to 1991 in the southern hemisphere's subtropical ridge which should be associated with a poleward trend in cold frontal activity and so reflect a reduction in frequency of cold outbreaks. This may contribute to the reduction in cold occurrences of lower tropospheric temperatures during the same period depicted in Fig. 10.

Local urbanisation in Tasmania's highlands has not been sufficient to have any effect on snowfall but the decline in snow settling to lower levels may be associated with the climatic factors mentioned above, i.e. an overall trend of warming and drying, but with some reversal in the warming during the period 1992 to 1996.

Conclusion

Snowfall may occur in any month in Tasmania, but the months July to September inclusive show a marked maximum. Cold outbreaks with snow, defined as the passage of a cold front with snow settling to below 600 metres, are most frequent in these months also, with no occurrences recorded during the summer months December to February. Cold outbreaks are not necessarily coincident with maximum temperatures in the lowest percentile range for any of the sea level meteorological stations in Tasmania, nor can quantity of precipitation over a 24-hour period be used to identify them. The parameters 850 hPa temperature, freezing level, 500 hPa temperature and 1000-500 hPa thickness can be used to differentiate between air masses likely to be associated with cold outbreaks with snow and less extreme weather. Longer period cold spells tend to be associated with a colder troposphere below 500 hPa than do shorter ones and most cold spells last only 1 to 3 days.

Based on the analyses presented here, an alternative categorisation of cold outbreaks is proposed, based primarily on upper air parameters.

In this categorisation, a 'cold outbreak' is defined as the passage of a cold front where the coldest air in the post-frontal air mass has the following typical properties:

- A mean 1000-500 hPa thickness of 2 standard deviations (10 gpdm) below the winter mean of 539 gpdm;
- A mean 850 hPa temperature at least 1.1 standard deviations (3°C) below the winter mean of 0.3°C;
- 500 hPa temperature at least 1 standard deviation (3.5°C) below the winter mean of -25°C; and
- freezing level at least 1 standard deviation (510 m) below the winter mean of 1490 m.

A 'cold outbreak with snow' has the additional criterion that snowfall settles to 600 m or lower which is near 1.7 standard deviations (870 m) below the mean winter freezing level (1490 m).

A 'cold outbreak with snow to low levels' is defined as the passage of a cold front where the post-frontal air mass has the following properties:

- 1000-500 hPa thickness at least 2.5 standard deviations (13 gpdm) below the winter mean value of 539 gpdm;
- 500 hPa temperature at least 2 standard deviations (7°C) below the winter mean of -25°C;
- 850 hPa temperature at least 1.8 standard deviations (5°C) below the winter mean of 0.3°C; freezing level at least 1.5 standard deviations (770 m) below the winter mean of 1490 m; and
- snowfall settles to 200 m or lower which is near 2.5 standard deviations (1280 m) below the mean winter freezing level of 1490 m.

Further study, including that of the influence of moisture profiles, is needed in order to delineate objectively, using upper air parameters, cold outbreaks with snow from non-severe cold outbreaks (producing less significant snow).

The frequency of cold outbreaks with snow declined over the 40-year period to 1996, the most marked decline being during the 1980s. The frequency of cold occurrences of the lower troposphere as measured by the above parameters also declined to 1990, but then increased again during 1992 to 1996. The decline in cold outbreaks with snow may be associated with this reduction in cold occurrences of the lower troposphere as well as reduced precipitation, rises in ocean temperatures surrounding Tasmania and rises in surface air temperatures over Tasmania.

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The interest and suggestions of Dr. T. Gibson and Prof. W. Budd at the Antarctic CRC, University of Tasmania are greatly appreciated.

Appendix

Listing of High Altitude Stations in Tasmania

Name	*Elevation (m)*	*Years of operation used in study*
Tarraleah Works	589	1982-1996
Butlers Gorge	666	1962-1992
Cradle Valley	920	1967-1976
Liawenee	1070	1987-1996
Mt Wellington Summit	1260	1962-1971

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