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# The Decline of Snowpatches in the Snowy Mountains of Australia: Importance of Climate Warming, Variable Snow, and Wind

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## Abstract

As with glaciers, long-lasting snowpatches have measurable features that are likely to be affected by a warming climate. Changes in these snowpatches are important as they often affect the down-slope thermal regime, water supply, nutrients, soil development, and vegetation. Australia's longest-lasting snowpatches, occurring in the Snowy Mountains, are formed during northwesterly winds, being deposited on southeasterly slopes where they are protected from insolation. Longevity of snowpatches is determined by winter snow and summer temperatures, with 155 days variation in the date of thaw among years. Snowpatches generally occurred in the same locations annually, but differences in direction of the winds during deposition affected snowpatch formation, accumulating aspect, and spatial melt patterns among years. Date of thaw of snowpatches was related to the general snowpack that has declined significantly over the past 54 years. Snowpatches previously multi-year in duration, melted in 2006 in the same year that they formed. Australian snowpatches have already declined with the resultant loss of specialized vegetation. Trends in reducing amount of snow and earlier thaw cast doubt on the long-term future of these snowpatches and their specialized plant communities.

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## Introduction

High mountain environments are among those most threatened by climate change (Grabherr et al., 1994). Reductions in snow cover and rising temperatures have been documented for many high mountain areas (Beniston, 2003). In temperate areas, snowpatches are a useful index of climate change, integrating climatic inputs in both short and medium time spans (Watson et al., 1994). These snowpatches may last throughout summer and initiate nivational processes (Goudie, 1994). They are ecologically important, reducing the length of the growing season and hence the plant species that can survive beneath them. They provide late summer water to vegetation communities down slope, accumulate nitrogen that is released during the growing season, and provide a steep environmental gradient over a short distance resulting in poor soil development at the center and changes in plant productivity across the gradient of snow melt (Billings and Bliss, 1959; Bowman, 1992; Björk and Molau, 2007). Within alpine areas there are specialized plant species and communities restricted to sites where snow cover remains weeks or months after the general thaw, that will be threatened by loss of snow cover with climate warming (Billings and Bliss, 1959; Björk and Molau, 2007).

The snowpatches in the Snowy Mountains of southeast Australia (36°27′S, 148°16′E) occur in areas receiving least sun (south to southeast aspects) that are in the lee of the predominantly northwesterly snow-bearing winds (Davis, 1998). Hence, the process of snowdrift and lowered insolation reinforce each other to create large snowpatches that have, in the past, remained continuously for "several years" (McLuckie and Petrie, 1927), have reached depths of 30 m (Costin et al., 1973), and have had appreciable nivation effects occurring in those snowpatches that commonly lasted longer than 245 days (Galloway et al., 1998). These snowpatches are the longest lasting in Australia, with snowpatches in the Victorian Alps and alpine Tasmania generally melting by late January (Wahren et al., 2001; Jamie Kirkpatrick, personal communication, 2007).

The alpine region of southeastern Australia has warmed over the past 35 years at a rate of about 0.2 K per decade, with projections for 2050 of a further increase of 0.6–2.9 K with possible reductions by 96% in the area sustaining snow cover for more than 60 days per year (Whetton, 1998; Hennessy et al., 2003). These changes in the amount and duration of snow cover are likely to affect the location and duration of snowpatches and their associated biota. However, there is limited research documenting the current extent of snowpatches and the factors that may affect their formation and melt. The aims of the present study were, therefore, to characterize the current state of the latest lying snowpatches in Australia (that is, those occurring in the Snowy Mountains), to determine the processes that result in the formation and melt of snowpatches and the variation in melt patterns, and to determine how Australian snowpatches have changed and/or are likely to change with a warmer, drier climate.

## Methods

*Ad hoc* records of the presence of snowpatches on the highest areas of the Snowy Mountains were kept over the past 10 years. Additionally, an attempt was made each year to document the 20 longest-lasting snowpatches. However, because of their spatial spread this was not always possible.

For more detailed study, seven of the 31 snowpatches extant in mid February 2004 were chosen, (see Fig. 1 for numbered snowpatches). These were: Twynam Cirque (1), Blue Lake Cirque north (6) and south (7), Club Lake Cirque (11), Mawson Cirque




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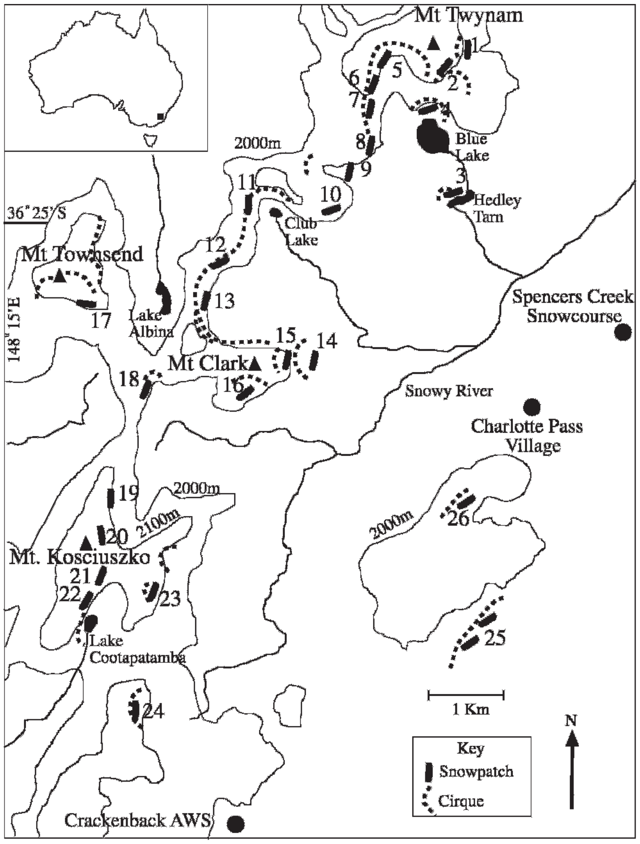


**FIGURE 1. Map of study area showing the sites of all snowpatches in February 2004 and three additional snowpatches occurring in December 2006. Major drainage lines and the 2000 and 2100 m contours are shown. The five water bodies all exist in glacial features. Cirque boundaries are based on Galloway et al. (1998) and Barrows et al. (2001).**

(12), the northeast ridge of Mt. Kosciuszko (19), and the Cootapatamba Cornice (22). Aspect was generally east to southeast on slopes of >25% up to nearly 50%.

## *SNOWPATCH ACCUMULATION*

To examine patterns of snow accumulation in different years, several sources of climatic data were used. Snow data came from the longest continuously recorded Snowy Hydro snow course in the region, at Spencers Creek (1830 m a.s.l.) (Fig. 1). To reflect both depth and duration of snow cover, these data were transformed into meter-days of snow by multiplying the depth of snow by the numbers of days at that depth and summing the weekly result to give a single figure for each year. To examine snow accumulation, the weekly snow depth at Spencers Creek was subtracted from that of the following week. Any increase of ≥10 cm was recorded as a "snow accumulation event." Data collected by us from the Whites River snow course (1680 m a.s.l., 13 km to the northeast of Spencers Creek) were compared to Spencers Creek to establish whether the accumulation events were widespread.

To determine conditions during days of snowfall, data from the Bureau of Meteorology stations at the Crackenback automatic weather station (AWS), Charlotte Pass ski village, and Perisher Valley ski village (located 6 km to the northeast of the Spencers Creek snow course) were used (Fig. 1). Hourly wind speed and direction in the seven days leading to the recording of snow accumulation events came from the standard 10 m height from the Crackenback AWS (Fig. 1). Six m sec$^{-1}$ is the lowest 10 m height wind speed at which snow transport will occur (Sturm et al., 2001, and references therein). Hence, hourly wind speeds ≥ 6 m sec$^{-1}$ were allocated to eight points of the compass, NW, N, NE, etc. Northwesterly winds lie between 292.5 and 337.5°, but because wind direction was recorded to the nearest 10°, this was effectively 290–330°. Because of the predominance of northwesterly winds, finer resolution of these winds was obtained by reallocating winds of 290–310° to WNW and 320–340° to NNW. Standard air temperature data came from the Crackenback AWS.

## *SNOWPATCH DECAY*

The dates of thaw of the seven monitored snowpatches were recorded after the winters of 1996, 1999, 2001, and 2003–2008. From summer 2004/2005 to summer 2006/2007 the decay rates of the seven snowpatches were measured using a hand-held GPS. In summer 2004/2005 the planar area of the Cootapatamba Cornice snowpatch was measured six times from March to the end of April. In 2005/2006 and 2006/2007 all seven snowpatches were measured each 14 days from the time they first became an entity, a minimum of three times or until they disappeared. This latter date was aligned for graphical purposes so that comparison of decay rates could be facilitated. The lines of best fit for the data for snowpatch area against time were plotted in Microsoft Excel as a second-order polynomial.

## *SOIL TEMPERATURES BENEATH SNOWPATCHES*

Soil temperatures were recorded from the center to the edge of the seven snowpatches. These sites were identified visually as (1) the center of the snowpatch where vegetation was usually absent, (2) down slope at the point where vegetation conformed to the classification short alpine herbfield (a vegetation type dependent upon the existence of snowpatches), and (3) in tall alpine herbfield that indicated that snow duration was short-lived after the thaw of the general snowpack (Costin et al., 2000). A Tinytag Plus temperature logger (Tinytag plus—Gemini Data Loggers, Chichester, England) recording at 120-minute intervals was buried beneath approximately 75 mm of soil in the three zones of each of the snowpatches. Vegetation cover was assessed visually for three 1 m$^2$ quadrats per snowpatch. This is the same as the methods currently used in the Global Observation Research Initiative in Alpine Environments (see http://www.gloria.ac.at). To ensure adequate sampling of species richness, all species were recorded in an additional two 1 m$^2$ quadrats on either side of each of the original three quadrats, making a total of 15 m$^2$ per zone per snowpatch.

The commencement of the snow-free season was a relatively easy point to find in the temperature trace because snow thaws in a warming environment, which causes fluctuation in the trace (see Körner and Paulsen, 2004). Within this period of fluctuation, the actual day of thaw was determined as when the temperature first rose above 3.2 °C at noon or within two hours either side of noon. The commencement of the snow season was harder to pick from the temperature trace (except in 2003/2004) because snow fell in a cooling rather than a warming period. However, the end of the snow-free season was calculated in a similar fashion to the commencement and was the point at which the noon temperature ±2 hours fell below 3.2 °C and remained below that level.

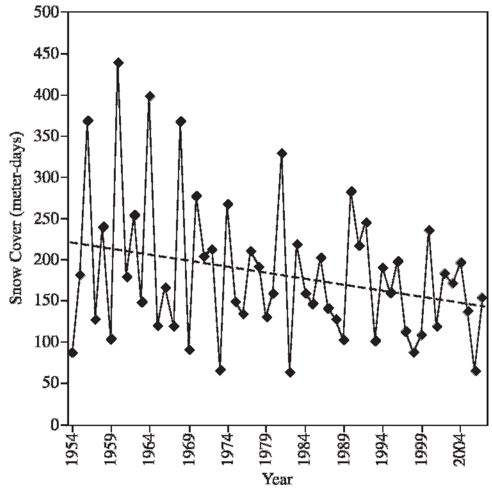


**FIGURE 2. Snow data for Spencers Creek snow course (1830 m a.s.l.), 1954–2007. To reflect both depth and duration of snow cover, data were transformed into meter-days of snow by multiplying the depth of snow by the numbers of days at that depth and summing the weekly result to give a single figure for each year.**

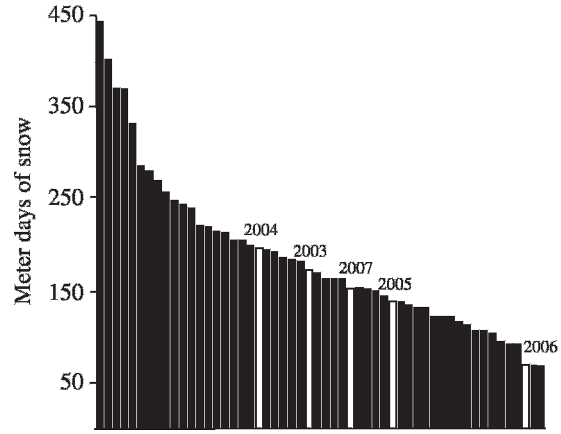


**FIGURE 3. Years 1954–2007 ranked from highest to lowest in terms of meter-days of snow at Spencers Creek showing the years when snow-free season was calculated for snowpatches.**

## Results

### *CHANGES IN SNOW COVER OVER THE PAST 54 YEARS*

In the 54 years that snow data have been collected at the Spencers Creek snow course there has been a significant decrease in snow ($r = -0.273$, $P < 0.05$). Snow cover has declined on average by 15 meter-days per decade, from an average of 213 in the first 10 years of measuring to only 146 m in the last 10 years (Fig. 2). There was no significant change in the absolute thaw dates, but there was a significant decline in the 5 year running average for thaw dates ($r = -0.532$, $P < 0.001$), with thaws occurring on average two days earlier per decade. Paralleling changes in snow cover and thaw date, there have also been significant declines in variation among years in these variables ($r = -0.502$, $P < 0.001$ for meter-days; and $r = -0.401$, $P = 0.003$ for thaw date). In the first 10 years of measurements, snow cover varied 335 meter-days between successive years, while in the last 10 years, the maximum variation between any 2 years was 127 meter-days. Similarly, in the first 10 years there was an average of 30 days variation between thaw date in successive years; in the last 10 years it was 14 days.

The general study period fell in years in the mid to low range for snow cover and thaw dates; 2003 and 2004 represent mid snow years in terms of snow amount (Fig. 3) and were ranked 35th and 36th of 54 years for date of thaw. Very low snow years were represented by the two earliest thaws on record in 2006 and 1999, which were third- and tenth-lowest years for snow amount (Fig. 3).

### *CONDITIONS ASSOCIATED WITH SNOW ACCUMULATION*

Over the five years studied intensively, the number of snow events contributing to the accumulation of the Spencers Creek snow course varied between four and eight (Table 1). Apart from the first one or two of these each year (when snow may not have fallen to lower altitude), most were also discernible at the Whites River snow course.

On days when precipitation was recorded in the week before the recording of snow accumulation events at Spencers Creek, the direction of wind $\geq 6$ m sec$^{-1}$ at 10 m above ground was predominantly northwesterly. This direction accounted for approximately two-thirds of wind in winter 2003 and 2005 and three-quarters in 2004 and 2006, but less than 50% in 2007 (Table 1). There was no significant difference between the distribution of wind on days with precipitation and all days within the week before the recording of snow accumulation events (Paired $t$-test, $t = 0.0$, df $= 39$, $p = 1.000$).

Although winds were predominantly northwesterly, when these winds were reallocated, about 50% were allocated to each of WNW and NNW in 2003 and 2005 (53% and 50% NNW respectively). By contrast to these two years, 2004 and 2006 were very different with an apparently stronger NW orientation of the winds (Table 1). On reallocation, 2004 had 59% of NW winds from the WNW and 2006 had 63% from the NNW. The year 2007 differed from all years with a much weaker NW orientation owing to a strong component from the SE; however, like 2004, 2007 had 59% of NW winds from the WNW.

### *SNOWPATCHES*

There was variation in the location and extent of the latest-lying snowpatches and in how long they lasted. Although the general location of some snowpatches was consistent from year to year, others were variable. On 14 February 2004, 30 snowpatches were present at 23 locations numbered in Figure 1. All of the last 16 snowpatches present in late January 2006 were at these locations. In early March 2005, however, of the last ten extant snowpatches, one (number 9) was at a site not occupied by a snowpatch in 2003/2004, nor in 2005/2006. In late 2006, this and two others (3 and 10) not found in any of the previous three years were recorded among the final 24 snowpatches (Fig. 1). Although 2007 had the second earliest thaw of snowpatches it differed from 2006 in gaining late-lying snowpatches at lower sites 14, 15, and 26 but losing them earlier at higher sites 5, 18, 20, and 21.

There was a significant relationship between date of thaw of the seven late-lying snowpatches and meter-days of snow at the Spencers Creek snow course ($r = 0.78$, $P < 0.0001$) (Fig. 4). The duration of the latest-lying snowpatches was highly variable among years (Fig. 4). For example, snow from winter 1996 was still present in late May 1997 when the new snowpack established. In contrast, all but one snowpatch from winter 2006 disappeared by late December 2006. Even this final snowpatch (number 23) only lasted into the first 10 days of 2007. The interannual

TABLE 1

**Number of snow accumulation events (all weekly increases in snowpack of ≥10 cm at Spencers Creek) and mean ± standard deviation increase in snowpack depth. The percentage distribution of direction of winds ≥6 m $sec^{-1}$ on days with precipitation in the week before snow accumulation events.**

| Year | 2003 | 2004 | 2005 | 2006 | 2007 |
|---|---|---|---|---|---|
| Events | 8 | 6 | 4 | 5 | 5 |
| Average increase (cm) | 28.6 ± 16.5 | 37.5 ± 15.1 | 48.3 ± 8.3 | 16.8 ± 5.0 | 28.6 ± 20.6 |
| Wind direction (%) | | | | | |
| E | 0.0 | 0.0 | 0.0 | 1.4 | 2.0 |
| NE | 0.0 | 0.0 | 1.0 | 0.0 | 0.0 |
| N | 4.9 | 1.1 | 7.2 | 3.4 | 0.6 |
| NW | 66.2 | 78.9 | 67.4 | 74.0 | 48.8 |
| W | 11.3 | 15.6 | 11.3 | 9.4 | 18.6 |
| SW | 8.2 | 2.5 | 5.8 | 3.4 | 5.3 |
| S | 9.5 | 1.8 | 7.0 | 6.3 | 8.0 |
| SE | 0.0 | 0.0 | 0.5 | 2.0 | 16.7 |

difference in the last date that snow was observed for the seven studied snowpatches was of the order of 155 days. By contrast, the difference in the last date that snow was recorded at the Spencers Creek snow course for the same nine years was 45 days. In 2006, there was only about one-third the amount of snow as for 1996.

There was also variation in the microtopographic position in which snow lay longest. At the Cootapatamba Cornice, the snowpatch was located in the same area over three years (2004/2005 to 2006/2007) and decayed in essentially the same way. However, in 2003/2004, the snowpatch was divided with snow located to the north and south of the center. This meant that the later snow, outside the normal catchment boundary, contributed little moisture to the snowpatch vegetation beneath. A similar situation occurred at Twynam Cirque, where the more easterly facing snowpatch to the north of the main patch irrigating the snowpatch vegetation disappeared earlier in 2005/2006 but remained after the main snow patch in 2006/2007. The Blue Lake south snowpatch contracted to a central point on a southeastern aspect in 2005/2006. However, in 2006/2007 it contracted to the same southeastern aspect, but also on a separate easterly aspect.

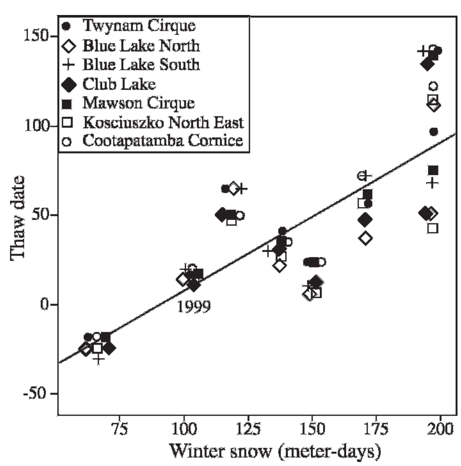


**FIGURE 4. Regression of the last date recorded of presence of the seven late lying snowpatches on meter-days of snow at the Spencers Creek snow course ($r = 0.78$, $P < 0.0001$). Thaw date is Julian days from January 1, hence it is positive when it occurs after January 1 and negative when it occurs in the winter in which the snow accumulated. Data for the year 1999 were not used in the regression because of lack of precision in recording the last day snowpatches were extant.**

The rate of decay differed among snowpatches and years (Fig. 5). Decay rates were generally faster in 2005/2006 among the snowpatches with larger surface areas (Blue Lake north, south, and Mawson Cirque) but slower in snowpatches with smaller surface areas (Twynam Cirque, Cootapatamba Cornice, and Kosciuszko NE), with the Club Lake Cirque snowpatch intermediate. In 2006/2007, decay rates were slower than in 2005/2006 except at Twynam Cirque. This was associated with the earlier date of thaw because the snowpatches in 2006/2007, although melting earlier, were doing so more slowly in a cooler environment (Table 2). A similar situation occurred at Cootapatamba Cornice, where the snowpatch decayed slowly in the cooler months of March to May after the hottest months of summer had passed (January and February).

Based on data from the temperature loggers, in the three summers 2003/2004 to 2005/2006 the mean snow free period in the center of the snowpatches was 72 ± 17.0 days. In 2006/2007, however, the mean snow free period in the center was 193 ± 18.0 days (Table 3). Based on the amount of winter snow in the preceding winter (Fig. 3), what happened to snowpatches in 2003/2004 and 2004/2005 could be considered characteristic of medium snow years, whereas what happened in 2006/2007 could be

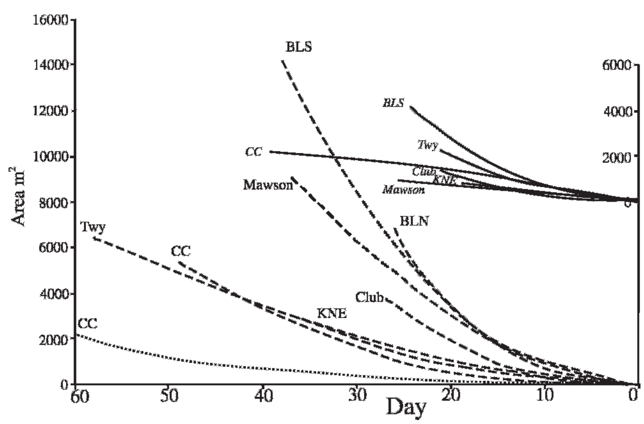


**FIGURE 5. Decay rates for the seven studied snowpatches in 2005/2006 (dashes) and 2006/2007 (solid lines) together with 2004/2005 (dotted line) for the Cootapatamba Cornice only. The *y*-axis on the right is at the same scale as on the left but is raised higher to distinguish the lines for 2006/2007 for both sets of graphs. BLS = Blue Lake South, Twy = Twynam Cirque, CC = Cootapatamba Cornice, Club = Club Lake, KNE = Kosciuszko Northeast, Mawson = Mawson Cirque, and BLN = Blue Lake North.**

TABLE 2

**Days required in 2006/2007 for snowpatches to decay to zero from the first measurement (square meters), together with the average maximum and minimum temperatures (°C) for that period. The dates for the equivalent starting point for 2004/2005 and 2005/2006 were calculated from equations for the decay lines in Figure 5.**

| | From | To | Days | Av max Temp. | Av min Temp. |
|---|---|---|---|---|---|
| Twynam Cirque (1675 $m^2$) | | | | | |
| 2005/2006 | 20 Jan | 15 Feb | 26 | 18.87 | 9.56 |
| 2006/2007 | 24 Nov | 5 Dec | 12 | 17.18 | 6.08 |
| Blue Lake south (4158 $m^2$) | | | | | |
| 2005/2006 | 19 Jan | 5 Feb | 18 | 20.39 | 11.73 |
| 2006/2007 | 24 Nov | 16 Dec | 23 | 16.92 | 5.91 |
| Club Lake Cirque (1136 $m^2$) | | | | | |
| 2005/2006 | 9 Jan | 26 Jan | 18 | 18.93 | 10.52 |
| 2006/2007 | 23 Nov | 12 Dec | 20 | 17.76 | 6.41 |
| Mawson Cirque (725 $m^2$) | | | | | |
| 2005/2006 | 24 Jan | 5 Feb | 13 | 20.68 | 12.07 |
| 2006/2007 | 22 Nov | 16 Dec | 25 | 16.85 | 6.08 |
| Kosciuszko NE (616 $m^2$) | | | | | |
| 2005/2006 | 21 Jan | 5 Feb | 16 | 20.99 | 12.51 |
| 2006/2007 | 22 Nov | 10 Dec | 19 | 17.84 | 6.64 |
| Cootapatamba Cornice (2099 $m^2$) | | | | | |
| 2004/2005 | 3 Mar | 2 May | 60 | 11.42 | 3.08 |
| 2005/2006 | 15 Jan | 17 Feb | 33 | 18.33 | 9.36 |
| 2006/2007 | 16 Nov | 22 Dec | 36 | 16.51 | 5.46 |

considered what might become more common, as winter snow amount declines. The 193 day snow free period in the center in 2006/2007 greatly exceeded the average 153 day snow free period occurring in tall alpine herbfield in the "medium" snow years. The vegetation cover for the three zones varied from 10.2% in the center of the snowpatches to 94.6% in the tall alpine herbfield. There were 13 vascular plant species found beneath the center of snowpatches with the highest number found in short alpine herbfield (Table 3), together with the highest number of species endemic to the Mt. Kosciuszko alpine area (7 compared to 2 in tall alpine herbfield).

## Discussion

The Snowy Mountains at 36°S have maritime snow (Sturm et al., 1995; Sanecki et al., 2006) that metamorphoses quickly and is, therefore, denser and less liable to be moved by wind. Therefore snowdrift, the drift occurring during snowfall (Watson et al., 1994), is probably more important than wind-drift (redistribution of the snowpack) in the formation of snowpatches. The predominant wind direction in the Snowy Mountains during snowdrift is northwest, such that snowpatches preferentially form on southeast slopes where insolation is least. This provides a southern hemisphere mirror image of the situation in Scotland (Watson et al., 1994). The snowdrifts in the Snowy Mountains form during only a few snow accumulation events each year, similar to the five to eight in a typical winter in arctic Alaska (Table 1; Sturm et al., 2001). The general correspondence of snow accumulation events at Spencers Creek snow course and Whites River, some 13 km away and 150 m lower, suggests that these events are widespread and synoptic in origin rather than local effects. Because the Snowy Mountains are at the northern extent of the influence of mid-latitude fronts, the possible movement of circulating weather pattern southwards with a change in climate could mean that the direction of prevailing winter winds in regard to snowdrift may change. This would have the effect of redistributing the snowpatches to different sites and aspects, possibly exposing them to greater summer insolation and having serious implications for the current snowpatch vegetation.

In Scotland, snow patches are sensitive to annual changes in climate, and similar responses could be expected in other mountain areas with oceanic climates (Watson et al., 1994). In the Snowy Mountains, with essentially maritime snow (Sanecki et al., 2006), the formation and decay of snowpatches was not only sensitive to amount of snow and wind direction, but also summer warmth. This latter is in contrast to the findings of Watson et al. (1994) in Scotland where there was no significant relationship between survival of snowpatches from month to month and the climate for that month, with a uniform loss rate across years. By contrast, snowpatches in the Snowy Mountains melted quicker in

TABLE 3

**Mean (± standard error) of snow-free season days beneath the center of snowpatches, in short alpine herbfield (SAH), and tall alpine herbfield (TAH) over four summers 2003/2004 to 2006/2007, together with the percentage cover of vegetation and number of plant species beneath the zones.**

| Zone | Season days 2003/2004 | Season days 2004/2005 | Season days 2005/2006 | Season days 2006/2007 | Vegetation cover (%) | # Plant species |
|---|---|---|---|---|---|---|
| Center | 76 ± 38 | 53 ± 34 | 58 ± 16 | 193 ± 18.0 | 10.2 ± 3.0 | 13 |
| SAH | 99 ± 32 | 94 ± 13 | 105 ± 11 | N/A | 77.5 ± 4.3 | 35 |
| TAH | 147 ± 25 | 159 ± 21 | 150 ± 25 | N/A | 94.6 ± 1.7 | 27 |

mid summer in 2005/2006, and although they melted earlier in summer 2006/2007, they did so in a cooler environment (Table 2), resulting in a slower decay rate. Similarly the autumnal decay at Cootapatamba Cornice in 2004/2005 was slower. It appears then that the longer the snowpatches last into the summer the greater is their rate of melt, until the heat of the summer is over and the rate of snowmelt declines. This suggests that there may be a tilting point in the seasons, and only by accumulating sufficient snow in winter and thereby passing that point is long-term survival of snowpatches guaranteed.

Alpine snow depth and the timing of melting are generally variable (Friedel, 1961; Körner, 1999; Hejcman et al., 2006). However, snowpatches in the Snowy Mountains appear to be more variable than those in other parts of the world with variation in melt dates among years during this study at around 22 weeks. Differences in timing of thaw of only three weeks in the earliest melting parts of snowpatches and two weeks in the latest melting parts were found in the mid alpine zone in northern Sweden (Björk, personal communication, 2007). Elsewhere differences in date of snow melt of "a week or more" have been found in Colorado (Stanton et al., 1994) while on the Beartooth Plateau of Wyoming/Montana differences of about five weeks were recorded (Johnson and Billings, 1962).

Whilst winter weather (precipitation, wind speed, and direction) affects the annual variation in snowpatch morphology, topography sets the general form and location of snowpatches on a longer term (Billings and Bliss, 1959; Hejcman et al., 2006). This long-term tenure of snowpatches is important for the establishment of specialist plant communities (Costin et al., 2000). Edmonds et al. (2006) concluded that snowpatches in the Snowy Mountains occurred in the same locations among years. However, this was not necessarily the case in the present study. There were differences between the winters of 2003 and 2005 in amount of snow, date of establishment of the snowpack, date of thaw, and number of accumulation events (Table 1). However, the distribution of wind direction during accumulation events was very similar (Table 1), and snowpatches in the following summer were consistent in their locations. By contrast to these two years, 2004 and 2006 had different distributions of wind resulting in persistence of snow on more easterly or southerly aspects respectively, while in 2007 there was a tendency for lower altitude snowpatches to survive longer whilst the highest snowpatches disappeared earlier.

Interannual snow depth variations in the Snowy Mountains are closely related to variations in the surface air pressure in the region (Nicholls, 2005), and variation in the latitude of synoptic systems can have a major influence on snow depth (Davis, 1998). This variation might also affect wind direction, which has not been factored into projections of the impacts of climate change for the Snowy Mountains, but could seriously affect alpine snowpatches. Galloway et al. (1998) calculated that for snowpatches in the Snowy Mountains to last 245 days (the time necessary for appreciable nivation effects to occur), snow falling on a site must be multiplied four times by drift and, with expected regional warming but no change to precipitation, must be multiplied six times to last the same time as currently. However, precipitation in the Snowy Mountains is expected to decrease by up to 24% by 2050 (Hennessy et al., 2003). The snow melted on the seven snowpatches in 2006 after only 203 days, an insufficient time for appreciable nivation effects to occur (Galloway et al., 1998). This also resulted in a snow-free growing period sufficient for the growth of the taller herbfield species, placing further pressure on the existence of specialized low growing snowpatch communities that are already declining (Green and Pickering, unpublished data). These specialized short alpine herbfield communities contain more endemic species and have a greater diversity of plant species than the invading taller herbfields that are largely dominated by grasses (Table 3).

Snowpatch vegetation communities and their constituent species are particularly at risk because they are limited spatially, being dependent upon the specific climatic and topographical conditions that result in the accumulation of deeper and longer lasting snow than at adjacent sites. They are dependent upon the regularity of deeper snow to exclude competition (Billings and Bliss, 1959; Björk and Molau, 2007). Among the snowpatches studied here, the snow free period in the center of the snowpatch, normally of the order of 70 days per year, increased to nearly three times that in 2006/2007 and exceeded the normal snow-free period of surrounding tall alpine herbfield by 42 days. This effectively removed the snow barrier to the invasion of tall alpine herbfield species into the center of some snowpatches as already documented (Green and Pickering, unpublished data). With the predictions for reduced snow cover in the Snowy Mountains, the annual variation will include more years such as 2006, with important implications for plant immigration. The additional function of snowpatches, the provision of summer meltwater to plant communities downhill, may also be breaking down, with variations in wind resulting in the latest snow in 2003/2004 and 2006/2007 lying outside normal drainage lines. In the Snowy Mountains, the snowpatches are therefore not only declining but also changing from the predictable to the unpredictable, and may no longer be a sufficient presence to have the major impact on soil and vegetation that they have in the past, leading to a breakdown in the pattern of long-documented vegetation communities.

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