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Source: Arctic, Antarctic, and Alpine Research, 38(3) : 429-435

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430(2006)38[429:TCACOA]2.0.CO;2

Arctic, Antarctic, and Alpine Research, Vol. 38, No. 3, 2006, pp. 429–435

The Characteristics and Classification of Australian Snow Cover: an Ecological Perspective

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Abstract

We provide a description of the structural and thermal characteristics of snow cover in the Snowy Mountains of southeast Australia. Using the snow classification system developed by Sturm et al. (1995), the snow cover in the Snowy Mountains is classified primarily as maritime in areas where there is sufficient accumulation, and as ephemeral at lower elevations and on ablating aspects. Maritime snow is generally deep ($>$100 cm), with a density $>$0.30 g cm^{-3}. The snow-ground interface is maintained within 1°C of freezing and relatively high air temperatures promote equitemperature metamorphism throughout the winter. The formation of depth hoar (temperature gradient snow), which is considered to be important in facilitating the development of the subnivean space, does not occur under these conditions. Ephemeral snow is characterized by warm shallow snow that often melts before new snow is deposited. Basal melt is a common feature of snow cover in the Snowy Mountains throughout most of the winter. We reappraise the processes responsible for the formation of the subnivean space under Australian snow conditions and discuss the importance of these processes for understanding the ecology of fauna in the subnivean space. Our findings highlight the value of an explicit description of snow conditions to ecological research in snow-covered areas. As a minimum, researchers should provide a description of basic structural and thermal properties of the snow pack that would allow other researchers to view the work in an appropriate context.

Introduction

The presence of snow in the landscape is a significant factor in the ecology of organisms (Formozov, 1946; Pruitt, 1960, 1984; Halfpenny and Ozanne, 1989; Green and Osborne, 1994; Stenseth et al., 2004). Despite the considerable literature on snow itself and, to a lesser extent, on its influence in the biosphere, the study of the ecological aspects of snow remains a relatively underdeveloped discipline (Halfpenny and Ozanne, 1989).

In Australia, the area subject to seasonal snow cover lasting at least 2 months comprises about 1675 km^2, or about 0.02% of the mainland. Nevertheless, Australian alpine and subalpine areas have developed a unique biota characterized by considerable endemism (Green and Osborne, 1994; Mansergh and Broome, 1994; Costin et al., 2000). As might be expected, snow-related research is less developed in Australia compared with regions where snow plays a much greater role in landscapes and the lives of human inhabitants. As a result, the understanding of snow ecology in Australia has been influenced by (and is to some extent reliant on) research undertaken overseas, especially in the northern hemisphere where studies are usually conducted at higher latitudes and/or elevations than in Australia. If the findings of these studies were transferred to an Australian context without consideration of variations in snow cover characteristics, the consequent misconceptions could affect the study of organisms that interact with snow at some point in their life cycles.

A further complicating factor is the tendency of research on snow as a physical phenomenon to be relatively divorced from considerations of snow as an ecological attribute. For example, although a number of workers have described meteorological and hydrological aspects of snow under Australian conditions (Costin et al., 1961; Brown and Millner, 1989; Davis, 1998)—the physical characteristics of Australian snow (Ruddell, 1998), the spatial distribution and duration of snow pack in the Australian Alps (Slatyer et al., 1984; Duus, 1992; Osborne et al., 1998), the effects of climate change (Ruddell et al., 1990; Whetton et al., 1996; Whetton, 1998) and the likely effects of climate change on the ski industry (Galloway, 1988; Konig, 1998; Hennessy et al., 2003)—few of these authors make more than a passing reference to the ecological implications of their findings. Conversely, in ecological research, snow cover is sometimes treated as if independent of local or regional influences, something that is clearly not the case (Berry, 1981; Mckay and Gray, 1981; Davis, 1998). Where ecologists have attempted to integrate snow as a factor into the study of alpine and subalpine biota (Green, 1982; Carron, 1985; Green, 1988; Bubela et al., 1991; Happold, 1998), some aspects of snow cover characteristics are described. However, researchers have not used their data to make meaningful comparisons between Australian snow cover conditions and those occurring elsewhere, especially those from regions from which we have derived so much of our understanding of nival ecology processes.

On a global scale, any possibility of misconception could be largely avoided by the widespread adoption of a scheme that facilitates cross-regional classification of snow cover, and in particular allows comparisons of the ecological attributes of the snowpack. While the systems of Magono and Lee (1966) and Colbeck et al. (1992) provide a framework for classifying snow based on crystal structure and other features, these systems are not useful for describing classes of snow cover at landscape scales (Sturm et al., 1995). Early attempts to devise large-scale snow classification systems did not gain wide acceptance because they were based upon different combinations of descriptors and consisted of different numbers of classes that did not necessarily correspond to classes in other systems; in general, they were often of little use beyond a local area. For a review and summary of these systems see Sturm et al. (1995).

Sturm et al. (1995) noted the need for a more generic system for classifying various types of snow cover. They developed a system

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which relies on observable snow cover properties and uses characteristics that are easily measured in the field or readily available from other sources.

This paper has two objectives. The first is to provide a brief description of the characteristics of Australian snow using data collected during the winters of 2002 and 2003. The second is to use these data supplemented by additional records to classify Australian snow according to the system developed by Sturm et al. (1995), hereafter referred to as the Sturm system, thus placing Australian snow cover in a more global context. We discuss some of the ecological considerations arising from our findings.

Methods

THE STURM CLASSIFICATION SYSTEM

The details of the Sturm system are given in Sturm et al. (1995). What follows is an overview of the system including the elements used for this paper.

The Sturm system has six main classes that Sturm et al. (1995) suggested generally reflect the natural grouping of snow cover characteristics. These include: tundra, taiga, alpine, maritime, ephemeral, and prairie (Figs. 1 and 2). A seventh "mountain" class is defined as a highly variable snow cover greatly influenced by varying solar radiation and wind patterns, often resulting in a number of different snow types within a relatively small area.

The names chosen for the classes, although referring to either a vegetation type or geographic location, do not imply that the classification is based upon the location of the snow cover or its relationship to a specific biome. The system relies solely on the physical characteristics of snow for classification; thus, "taiga" or "maritime" snow may occur in locations that are not taiga or close to the sea, respectively, but have characteristics of the particular snow cover type. For example, "taiga" snow cover is of thin to moderate depth, its stratigraphic profile is dominated by depth hoar (temperature gradient snow), and it exhibits few melt features. These characteristics reflect the particular conditions under which the snow was deposited and then remained. In the case of taiga snow cover, we would expect it to occur in cold climates with consistently low average winter temperatures. Taiga snow also would not be greatly affected by wind; a reflection of its tendency to occur in forested areas.

The advantage of the Sturm system is the use of average winter values for four variables (snow depth, air temperature, snow-ground interface temperature, and density) that are easily measured in the field, or available from routine snow course observations and weather stations. A fifth parameter, vertical temperature gradient, is based on a combination of snow depth and the difference between air and snow-ground interface temperature. The Sturm system does away with the need to dig snow pits and make repeated stratigraphic observations, which can be time consuming and often require special skills and equipment as required by the Colbeck et al. (1992) system.

THE STUDY AREA

Our study area was located within the Snowy Mountains, Kosciuszko National Park (36.0°S, 148.3°E) in southeast Australia. This region includes the Australian continent's highest mountain,

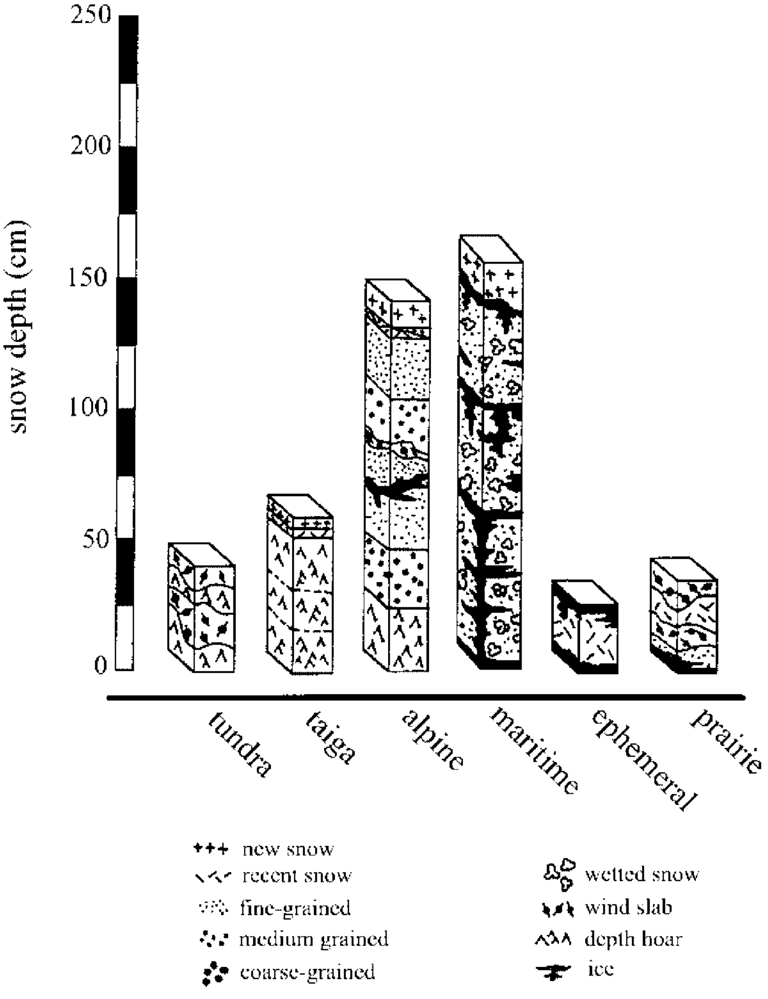

FIGURE 1. Stratigraphic and textural profiles of snow cover classes (from Sturm et al., 1995).

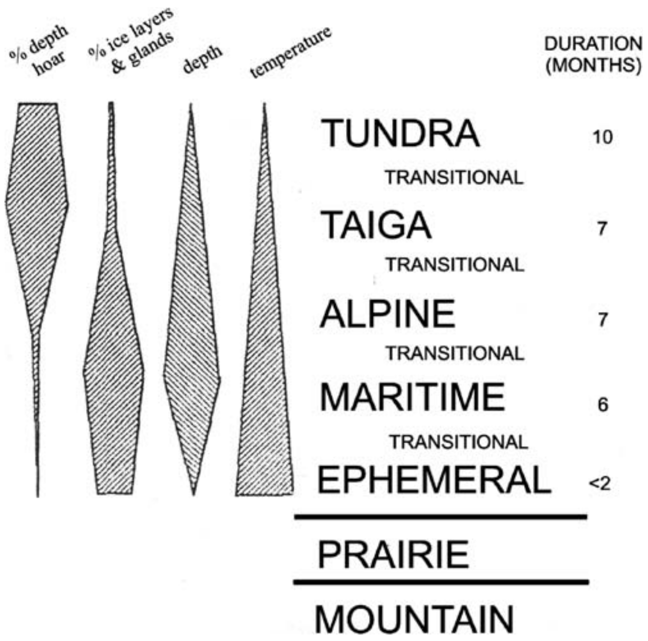

FIGURE 2. Attributes of snow cover classes (from Sturm et al., 1995).

Mount Kosciuszko (36.456°S, 148.264°E, 2228 m a.s.l.). The Snowy Mountains include most of the northern extent of the Australian Alps and encompass the largest contiguous areas of alpine and subalpine habitats on the Australian mainland.

The Australian Alps consist of a disjunct series of peaks and plateaux extending for about 350 km in a generally northeasterly direction from their southern extent at about 37.5°S, 146°E, to 35°S, 149°E (Fig. 3). Snow cover that remains on the ground for any length of time occurs in two main zones. The alpine zone, defined as the areas above the tree line, is characterized by continuous snow cover for at least four months per year. The subalpine zone lies between the upper limit of the tree line and the snowline at its lower limit. It is subject to continuous snow cover for at least one month (Green, 1998a; Costin et al., 2000). The tree line occurs at 1800–1900 m in the north, descending to 1750 m in the south. In a similar manner, the subalpine zone commences at a lower elevation in the south (around 1400 m) but occurs above 1500–1600 m in the north (Green, 1998b). The treeless alpine area has a diverse assemblage of vegetation communities, but is typically characterized by herbfields and heathlands (Costin et al., 2000). The subalpine area is a mosaic of woodlands dominated by snow gum, *Eucalyptus pauciflora*, wet and dry heathlands, and tussock grassland (Green and Osborne, 1994).

DATA COLLECTION

Data for this study were collected as part of a larger project investigating the distribution of small mammals in relation to snow cover in Kosciuszko National Park. These field measurements were supplemented with data obtained from routine snow course and meteorological records.

Snow depth measurements were made during 2002 at 72 sites, stratified across three elevation levels (1501–1600 m, 1601–1700 m, and 1701–1800 m) and two aspects (ablating and accumulating). Ablating aspects in Kosciuszko National Park are generally north-westerly and usually have lower snow depths than accumulating (southeasterly) aspects. This is because the latter are subject to lower insolation levels and, due to the prevailing northwesterly winds, act as a snow fence. Within each elevation and aspect, sites were selected to include the main vegetation types present. Of the 72 sites sampled in this study in 2002, 24 at the highest elevations were resampled in 2003.

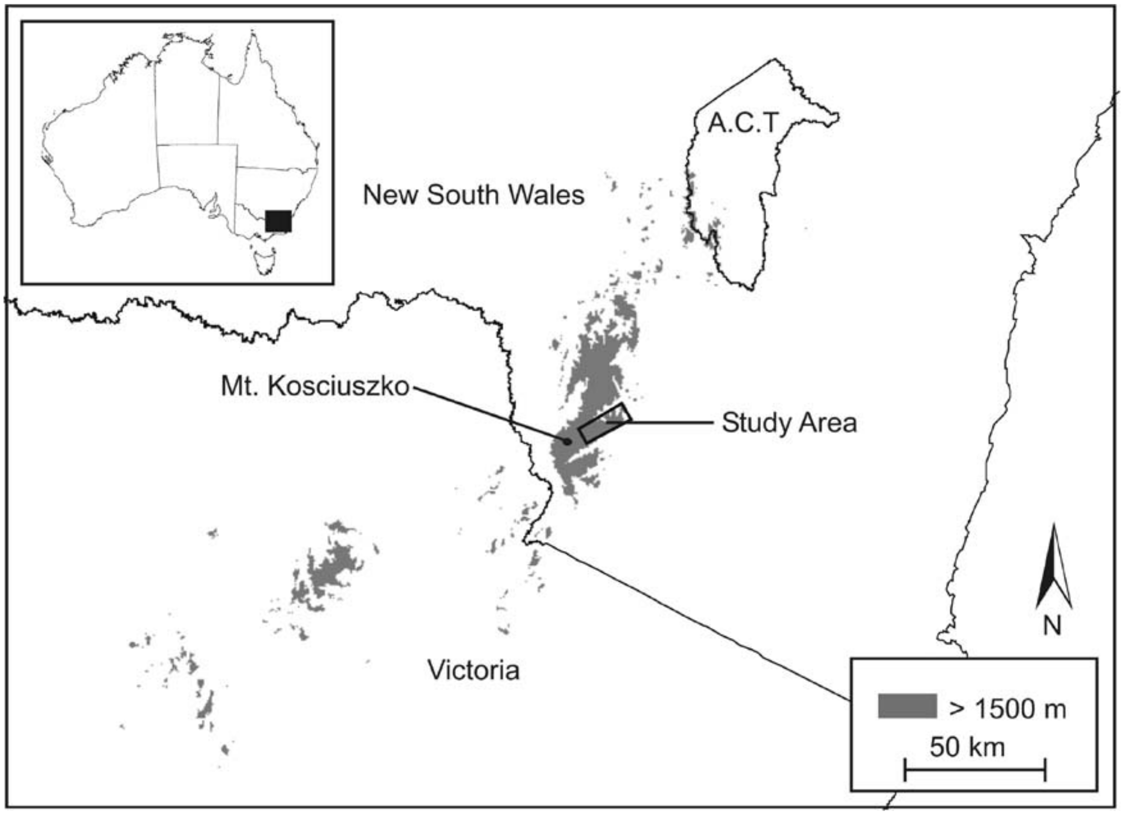

FIGURE 3. The Australian Alps, showing the area above 1500 m.

Each site comprised three plots approximately 10 m apart, each plot consisted of a 200 cm timber stake marked at 10 cm intervals to enable measurement of snow depth to the nearest 5 cm. Snow depth was recorded on a weekly basis during 2002 and at intervals of two weeks or one month during 2003. In addition, weekly snow depth data recorded at Spencers Creek snow course (36.43°S, 148.35°E, 1830 m) were obtained from Snowy Hydro Limited.

Winter average air temperatures for each of the study sites were derived from the ESOCLIM module of ANUCLIM 5.1 (Houlder et al., 2000). ANUCLIM generates climate estimates for selected locations from thin plate smoothing spline surfaces fitted to continent-wide monthly mean meteorological data using ANUSPLIN 4.3, producing estimates of monthly mean climate variables (Hutchinson, 1991, 2004). For temperature, ESOCLIM estimates are accurate to 0.5°C or better (M. Hutchinson, personal communication).

Seasonal average air temperature for Spencers Creek was calculated from data obtained from the Thredbo Crackenback Automatic Weather Station (AWS) (36.49°S, 148.29°E, 1957 m). Although about 8.9 km from the Spencers Creek snow course, this is one of only two stations from which regular long-term records are available for the study region. The other, located at Perisher Valley (36.40°S, 148.41°E), is closer to Spencers Creek (6.4 km), and located at an elevation of 1735 m. We considered that air temperatures taken from the higher station would provide more conservative calculations than the lower one.

During 2002, snow-ground interface temperatures were measured using 24 Thermocron® iButton temperature loggers (Dallas Semiconductor Corp.), located throughout the 72 study sites, giving 4 replicates of each elevation/aspect combination. Temperature loggers were installed at all 24 high elevation sites sampled in 2003. Loggers were held in white colored open-ended PVC tubes (56 mm × 27 mmø) and placed randomly within the study sites. The PVC tubes ensured that, irrespective of variations in the subnivean space size and the proximity of snow to the ground, none of the loggers were in direct contact with the basal snow layer. Loggers had a resolution of ±0.5°C and were set to record at 2 h intervals. Average temperatures were calculated for the period when continuous snow cover was present at a particular site.

Snow density data were available only for the Spencers Creek snow course where depth and bulk density measurements are taken on a weekly basis. Full profile density measurements were averaged for each month of winter and for the entire season. It is likely that snow density at field sites (all of which are at lower elevations than Spencers Creek) would equal or exceed the values at Spencers Creek, especially at lower elevations. This is because of higher rates of snow pack metamorphism, especially on ablating aspects where higher insolation often causes considerable melt-refreeze metamorphism (Mckay and Gray, 1981) (G. Sanecki, unpublished data). Therefore, the Spencers Creek data provide a conservative estimate of density.

The Sturm system is based on average winter values for each parameter. Previous studies (Carron et al., 1990; Bubela and Happold, 1993; Happold, 1998) have defined winter as being the time when "snow permanently covered the ground" from June to September. In this study, we have defined the winter period as occurring from June to August (92 days) and data from this period only were used for classifying snow classes.

Results

Table 1 summarizes the key snow cover characteristics of the three elevation classes sampled in this study. Despite the expected variations in snow depth and duration with vegetation type, aspect and elevation, and some year-to-year variations in depth and duration at the same site, there was little difference in snow/ground interface temperature among the sites. Average interface temperatures were consistently above freezing throughout winter regardless of air temperature. Snow-ground interface temperatures at Spencers Creek also were above freezing (Table 2).

As expected, air temperatures at the study sites decreased with increasing elevation. This temperature decrease was less than 1°C for each 100 m increase in elevation, corresponding to the temperature lapse rate of 0.6°C per 100 m. Average winter air temperature was above –2°C for the study sites (Table 1), and these estimates were consistent with data recorded at Thredbo AWS (Table 2, Spencers Creek).

Table 2 compares the Spencers Creek snow characteristics with those of the four main snow classes presented by Sturm et al. (1995). Spencers Creek was selected because it is one of the few sites from which long-term records are available, including snow density data. Characteristics of snow at Spencers Creek most closely resemble the maritime snow class. Sturm et al. (1995) noted that snow-ground interface temperatures for maritime snow are generally within 1°C of freezing and often display basal melt features which would be expected at temperatures above freezing. The vertical temperature gradient also most closely corresponds to the maritime class. Snow depth falls within the values expected for the maritime class, but also the alpine class. However, the latter exhibits a greater vertical temperature gradient resulting from lower average air temperatures. Spencers Creek air temperatures are in fact higher than the maritime air temperatures presented by Sturm et al. (1995). Snow density falls within the maritime range early in the winter (Fig. 4) but increases steadily throughout the season due to the progressive development of melt features and ice layers within the snow pack (G. Sanecki, unpublished data), producing a snow cover that is coarse grained and often wet. This is not only as a result of melt, but also rain, which can occur throughout the winter in the Australian Alps.

Sturm et al. (1995) described ephemeral snow as a thin, warm snow cover of short duration (<2 months) that often begins to melt shortly after deposition and is often subject to considerable basal melting. In this study, average winter air and snow-ground interface temperatures at the lowest elevation sites were above freezing throughout winter, suggesting conditions conducive to daytime snowmelt with intermittent nighttime freezing. Snow duration at all ablating and many accumulating low elevation sites was less than 2 months. In some cases, snow remained on the ground for only 2 weeks. Snow depth for all low elevation sites did not exceed 50 cm in depth. On ablating aspects at the mid-elevation level, there also were a number of sites where snow depth was less than 50 cm and duration was less than 2 months. We conclude that snow at low elevations should be classed as ephemeral. It is likely that at mid-elevations, and perhaps even higher

TABLE 1

Average values for snow cover during 2002–2003 on different aspects at three elevation levels in Kosciuszko National Park. Accum = accumulating aspects; Ablate = ablating aspects.

	1501–1600 m		1601–1700 m		1701–1800 m	
	Accum	Ablate	Accum	Ablate	Accum	Ablate
Air temp. (°C)						
June	0.8	0.9	0.4	0.4	–0.3	–0.4
July	–0.4	–0.3	–0.9	–0.9	–1.8	–1.8
August	0.5	0.6	–0.1	–0.2	–1.2	–1.3
Average	0.3	0.4	–0.2	–0.2	–1.1	–1.2
Snow/ground interface temp. (°C)	0.4	0.8	0.7	0.6	0.8	0.8
Maximum snow depth (cm)	48	35	83	71	118	116
Snow duration (weeks)	11.6	5.8	16.5	10.3	19.6	18.9

TABLE 2

Average winter values for Spencers Creek, Kosciuszko National Park, compared with the ranges of values for the main snow classes defined by Sturm et al. (1995).

	Tundra	Taiga	Alpine	Maritime	Spencers
Snow density (kg m^{-3})	250 to 320	200 to 220	240 to 280	260 to 330	360
Air temp. (°C)	−27.52 to −19.84	−19.92 to −13.86	−12.63 to −10.19	−9.62 to −4.53	−1.61
Snow/ground interface temp. (°C)	−22.00 to −8.45	−6.60 to −2.37	−1.28 to −0.49	−0.34 to 0.16	0.62
Snow depth (cm)	10.0 to 30.0	37.9 to 61.2	64.7 to 124.9	80.7 to 158.8	108.1
Vertical temp. gradient (°C m^{-1})	−59 to −39	−38 to −28	−22 to −12	−18 to −7	−5

elevations during some years, snow cover also may be ephemeral in nature, particularly on ablating aspects.

Discussion

Based upon the classification system of Sturm et al. (1995) and the data gathered in this study, snow cover at higher elevations in Australia most closely resembles maritime snow. However, since Australian snow displays some divergent characteristics, it is possible that snow of this type represents a separate "warm-temperate–tropical" category where daytime temperatures are above 0°C and nighttime temperatures below 0°C. These conditions favor equitemperature (ET) metamorphism and melt-freeze metamorphism as the dominant processes responsible for changes in the snow pack over time. It is likely that ephemeral snow occurs over at least half of the area subject to snow cover in the Snowy Mountains, based on snow depth and duration data presented by Slatyer et al. (1984).

There appears to be little merit to the argument that a mountain classification is more appropriate for Australian snow to account for variations due to topography and other factors. Mountain snow is highly variable over relatively small geographic scales. For example, different classes could be described on the opposite sides of a ridge, whereas our data show that snow cover characteristics are quite similar over a range of elevations and aspects.

Similarly, the alpine snow cover class of Sturm et al. (1995) is not appropriate in the Snowy Mountains because both air and snow-ground interface temperatures are considerably lower, while the temperature gradient is much greater, than values observed in this study. Our study did not consider data from elevations above 1800 m, which in the Snowy Mountains is the approximate position of the treeline and the boundary between the alpine and subalpine zone. On the Australian mainland the alpine zone accounts for approximately 7% of the area subject to the seasonal accumulation of snow (Good, 1992). It is possible that alpine snow occurs at higher elevations; however, we do not consider this to be likely (except possibly in years with exceptionally harsh winters), as data from snow courses in the alpine areas of Kosciuszko National Park show similar snow density trends to Spencers Creek (G. Sanecki, unpublished data). Moreover, incidental measurements taken at a range of high-elevation sites over a six year period indicate that snow-ground interface temperatures almost never fall below 0°C (G. Sanecki, unpublished data).

Observations from other locations in Australia are consistent with data from Kosciuszko National Park and indicate that our conclusions about snow classes in the Snowy Mountains can safely be extrapolated generally across the Australian Alps. Fifty-four years of records from the Rocky Valley snow course in the Bogong High Plains (1650 m, 36.87°S, 147.28°E) show similar snow densities to those at Spencers Creek (Fig. 5). In addition, the two sites have similar patterns of snow accumulation (Osborne et al., 1998). Snow pit investigations at the summit of Mount Buller (1809 m, 37.13°S, 146.42°E) showed snow pack temperatures were at, or only slightly lower than, 0°C (Ruddell, 1998). Average winter air temperatures also are consistent with, or higher than, those in Kosciuszko National Park (G. Sanecki, unpublished data).

In the past, a lack of information about Australian snow conditions has led to assumptions that data collected in boreal regions, where taiga snow cover is commonly encountered, accurately reflect the situation in Australian alpine and subalpine areas. For example, Green and Osborne (1994) suggested that in areas of limited plant cover, the subnivean space forms due to temperature gradient (TG) metamorphism whereby water vapor (formed by sublimation) is transported from the warmer lower snow levels to the cooler upper layers where it recrystallizes, resulting in the development of deep layers of low-density depth hoar. However, TG metamorphism and thus the formation of depth hoar requires the snow pack to be subjected to a vertical temperature gradient in excess of 10–25°C m^{-1} for about one week (Akitaya, 1974; Colbeck, 1983; Ruddell, 1998). This process is

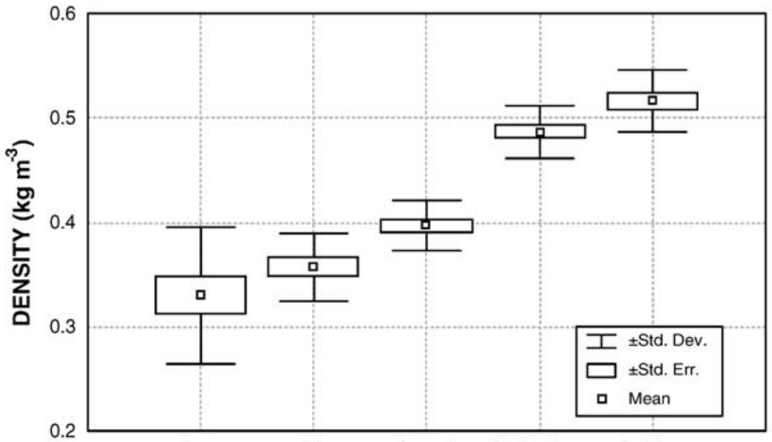

FIGURE 4. **Average snow density, 2002–2003, by month at Spencers Creek.**

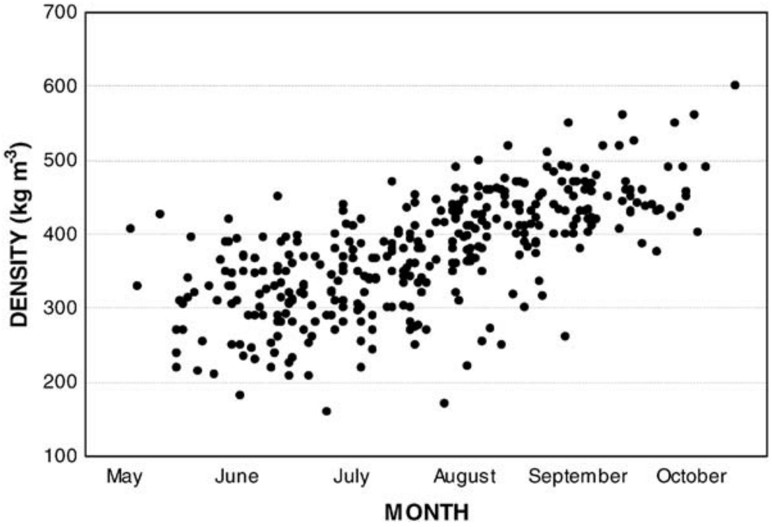

FIGURE 5. Average snow density at Rocky Valley snow course, 1935–1996 (after Ruddell et al., 1990; data source: Southern Hydro).

more characteristic of taiga snow (and alpine snow to a lesser extent). Data presented in this paper indicate that conditions conducive to the formation of taiga snow do not occur in Australia.

In the absence of a thermal gradient within a snow pack that is close to or just below 0°C, ET metamorphism becomes the dominant process for creating structure in the vertical stratigraphy (Langham, 1981; Ruddell, 1998). This type of metamorphism involves the transformation of snow crystals into more compact grains that, when combined by sintering processes, causes an increase in the hardness and density of the snow pack. As air temperatures increase and the snow pack further warms, melt-freeze metamorphism becomes predominant, further increasing snow pack density (Langham, 1981). These processes explain the relatively high density of Australian snow cover and the progressive increase in density throughout the nival period. The formation of the subnivean space in areas with little vegetation structure in Australia is probably related to basal melting processes as a result of snow-ground interface temperatures above 0°C.

Under suitable conditions the area of subnivean space can be quite extensive (Coulianos and Johnels, 1962) and it is thought that depth hoar is an important factor in the ecology of winter active subnivean fauna (Pruitt, 1984; Halfpenny and Ozanne, 1989; Auerbach and Halfpenny, 1991). A low-density depth hoar layer does not form in Australian snow fields. Rather, the typically high snow density is likely to provide a mechanical hindrance to small mammals that move under the snow. Snow density is above 300 kg m^{-3} throughout the snow profile for much of the season in Australia (Fig. 4) (Ruddell, 1998). However, small mammals have difficulty digging through snow with densities greater than 210 kg m^{-3} (Spencer, 1984). It follows that during winter in Australian alpine and subalpine regions, small mammals are confined to areas where physical processes other than TG metamorphism form a subnivean space of sufficient size to enable movement. The exception to this is early in the season or when fresh snow of low density permits tunneling (Green, 1998b) (G. Sanecki and K. Green, unpublished data). Similarly, any investigation of supranivean fauna would need to consider the implications of higher snow density and mechanical strength for the movement of fauna across the snow and their ability to dig into it.

Our study also has relevance to studies investigating the possible impact of snow compression by human activity, including the movement of over-snow vehicles or snow grooming on subnivean environments (Schmid, 1971; Keddy et al., 1979; Adam, 1981; Halfpenny and Ozanne, 1989; Green, 1998b, 2000). The nature of the impact is a function of the type of snow cover present at a particular site. Once it has achieved a certain depth, maritime snow has greater mechanical strength than ephemeral snow due to its depth and density. Consequently, it is probably less susceptible to compression for prolonged periods during the nival period, particularly mid- to late season (Langham, 1981).

Snow ecology needs more consistent snow classification. The Sturm system has been shown to provide a logical and practical paradigm for the description and interpretation of Australian snow cover conditions from an ecological point of view. However, the use of the Sturm system would also benefit from the inclusion of more global data to improve its generic applicability and strengthen its ecological significance.

Acknowledgments

This research was funded by the Department of Environment and Conservation (formerly New South Wales National Parks and Wildlife Service), which also allowed us to undertake this work within Kosciuszko National Park. Authority to conduct this research was provided by New South Wales National Parks and Wildlife Service (Scientific Investigation License no. B1963). The Centre for Resource and Environmental Studies at the Australian National University provided support and resources that permitted this work to be completed. Thanks to Karen Sanecki who has made many contributions to this work. Thanks to Allan Longstaff and Brian Reeves for assistance in the field. Thanks to Snow Hydro for providing access to snow course data. Thanks to Mike Hutchinson and Cade McTaggart for assistance in extracting climate averages from ANUCLIM.

References Cited

Adam, K. M., 1981: Travel over snow. *In* Gray, D. M., and Male, D. H. (ed.), *Handbook of snow; principles, processes, management and use.* Ontario: Pergamon Press, 521–561.

Akitaya, E., 1974: Studies of depth hoar. Institute of Low Temperature Science, Hokkaido University, Contributions from the Institute of Low Temperature Science, 1–67.

Auerbach, N. A., and Halfpenny, J. C., 1991: Snowpack and the subnivean environment for different aspects of an open meadow in Jackson Hole, Wyoming, USA. *Arctic and Alpine Research,* 23: 41–44.

Berry, M. O., 1981: Snow and Climate. *In* Gray, D. M., and Male, D. H. (ed.), *Handbook of snow; principles, processes, management and use.* Ontario: Pergamon Press, 32–59.

Brown, J. A. H., and Millner, F. C., 1989: Aspects of the meteorology and hydrology of the Australian Alps. *In* Good, R. B. (ed.), *The scientific significance of the Australian Alps: the proceedings of the first Fenner Conference.* The Australian Alps Liaison Committee/ Australian Academy of Science, 297–332.

Bubela, T. M., and Happold, D. C. D., 1993: The social organisation and mating system of an Australian subalpine rodent, the broad-toothed rat, *Mastacomys fuscus* Thomas. *Wildlife Research,* 20: 405–417.

Bubela, T. M., Happold, D. C. D., and Broome, L. S., 1991: Home range and activity of the broad-toothed rat, *Mastacomys fuscus*, in subalpine heathland. *Wildlife Research,* 18: 39–48.

Carron, P. L., 1985: *The ecology of three species of small mammals in subalpine habitat*. Ph.D. thesis. The Australian National University, Canberra.

Carron, P. L., Happold, D. C. D., and Bubela, T. M., 1990: Diet of two sympatric Australian subalpine rodents, *Mastacomys fuscus* and *Rattus fuscipes*. *Australian Wildlife Research,* 17: 479–489.

Colbeck, C. S., 1983: Ice crystal morphology and growth rates at low supersaturations and high temperatures. *Journal of Applied Physics,* 54: 2677–2682.

Colbeck, C. S., Akitaya, E., Armstrong, R., Gubler, H., Laeuille, J., Lied, K., McClung, D., and Morris, E., 1992: *The international classification for seasonal snow on the ground.* Hanover, New Hampshire: International Commission on Snow and Ice of the International Association of Scientific Hydrology/International Glaciology Society/USACRREL.

Costin, A. B., Gay, L. W., Wimbush, D. J., and Kerr, D., 1961: *Studies in catchment hydrology in the Australian Alps. III. Preliminary snow investigations*. Canberra: CSIRO, Division of Plant Industries Technical Paper no. 15.

Costin, A. B., Gray, M., Totterdell, C. J., and Wimbush, D. J., 2000: *Kosciuszko alpine flora*. Melbourne: CSIRO.

Coulianos, C. C., and Johnels, A. G., 1962: Note on the subnivean environment of small mammals. *Arkiv für Zoologie,* 15: 363–370.

Davis, C. J., 1998: Meteorological aspects of snow. *In* Green, K. (ed.), *Snow: a natural history; and uncertain future*. Canberra: Australian Alps Liaison Committee, 3–34.

Duus, A. L., 1992: Estimation and analysis of snow cover in the Snowy Mountains between 1910 and 1991. *Australian Meteorological Magazine,* 40: 195–204.

Formozov, A. N., 1946: Snow cover as an integral factor of the environment and its importance in the ecology of mammals and birds. Edmonton: Boreal Institute.

Galloway, R. W., 1988: The potential impact of climate changes on the Australian ski fields. *In* Pearman, G. I. (ed.), *Greenhouse: planning for climate change.* Melbourne: CSIRO.

Good, R. B., 1992: *Kosciusko heritage*. Hurstville: National Parks and Wildlife Service of New South Wales.

Green, K., 1982: Notes on winter-active invertebrates beneath the snow. *Victorian Naturalist,* 99: 144–146.

Green, K., 1988: A study of *Antechinus swainsonii* and *Antechinus stuartii* and their prey in the Snowy Mountains. Ph.D. thesis. The Australian National University, Canberra.

Green, K., 1998a: Introduction. *In* Green, K. (ed.), *Snow, a natural history; an uncertain future.* Canberra: Australian Alps Liaison Committee, xiii-xix.

Green, K., 1998b: A winter niche; the subnivean space. *In* Green, K. (ed.), *Snow: a natural history; an uncertain future.* Canberra: Australian Alps Liaison Committee, 125–140.

Green, K., 2000: Small mammal activity on the snow surface. *Victorian Naturalist,* 117: 214–218.

Green, K., and Osborne, W. S., 1994: *Wildlife of the Australian snow country.* Chatswood: Reed Books.

Halfpenny, J. C., and Ozanne, R. D., 1989: *Winter: an ecological handbook.* Boulder: Johnson Publishing Company.

Happold, D. C. D., 1998: The subalpine climate at Smiggin Holes, Kosciusko National Park, Australia, and its influence on the biology of small mammals. *Arctic and Alpine Research,* 30: 241–251.

Hennessy, K., Whetton, P., Smith, I., Bathols, J., Hutchinson, M., and Sharples, J., 2003: *The impact of climate change on snow conditions in mainland Australia.* Aspendale: CSIRO Atmospheric Research.

Houlder, D., Hutchinson, M. F., Nix, H. A., and McMahon, J. P., 2000: ANUCLIM Version 5.1. Centre for Resource and Environmental Studies, The Australian National University (http://cres.anu.edu.au/outputs/anuclim/php).

Hutchinson, M. F., 1991: The application of thin plate smoothing splines to continent-wide data assimilation. *In* Jasper, J. D. (ed.), *Data Assimilation Systems.* Melbourne: Bureau of Meteorology, BMRC Research Report no. 27, 104–113.

Hutchinson, M. F., 2004: ANUSPLIN Version 4.3. Centre for Resource and Environmental Studies, The Australian National University (http://cres.anu.edu.au/outputs/anusplin.php).

Keddy, P. A., Spavold, A. J., and Keddy, C. J., 1979: Snowmobile impact on old field and marsh vegetation in Nova Scotia, Canada—an experimental field study. *Environmental Management,* 3: 409–415.

Konig, U., 1998: Climate change and the Australian ski industry. *In* Green, K. (ed.), *Snow: a natural history; an uncertain future.* Canberra: Australian Alps Liaison Committee, 207–223.

Langham, E. J., 1981: Physics and properties of snowcover. *In* Gray, D. M., and Male, D. H. (eds.), *Handbook of snow; principles, processes, management and use.* Ontario: Pergamon Press, 275–337.

Magono, C., and Lee, C., 1966: Meteorological classification of natural snow crystals. *Journal of the Faculty of Science, Hokkaido University,* 2: 321–335.

Mansergh, I., and Broome, L., 1994: *The mountain pygmy-possum of the Australian Alps.* Kensington: New South Wales University Press.

Mckay, G. A., and Gray, D. M., 1981: The distribution of snow cover. *In* Gray, D. M., and Male, D. H. (eds.), *Handbook of snow; principles, processes, management and use.* Ontario: Pergamon Press, 153–190.

Osborne, W. S., Davis, M. E., and Green, K., 1998: Temporal and spatial variation in snow cover. *In* Green, K. (ed.), *Snow, a natural history; an uncertain future.* Canberra: Australian Alps Liaison Committee, 56–68.

Pruitt, W. O., Jr., 1960: Animals in the snow. *Scientific American,* 202: 61–68.

Pruitt, W. O., Jr., 1984: Snow and small animals. *In* Merritt, J. F. (ed.), *Winter ecology of small mammals.* Pittsburgh: Carnegie Museum of Natural History, Special publication no. 10, 1–8.

Ruddell, A., 1998: The physical properties of snow. *In* Green, K. (ed.), *Snow, a natural history; an uncertain future.* Canberra: Australian Alps Liaison Committee, 35–55.

Ruddell, A., Budd, W. F., Smith, I. N., Keage, P., and Jones, R., 1990: *The south-east Australian alpine climate study.* Meteorology Department, University of Melbourne, unpublished report to the Alpine Resorts Commissions.

Schmid, W. D., 1971: Modification of the subnivean microclimate by snowmobiles. *In* Haugen, A. O. (ed.), *Proceedings of the snow and ice in relation to wildlife and recreation symposium.* Ames: Iowa State University, 251–257.

Slatyer, R. O., Cochrane, P. M., and Galloway, R. W., 1984: Duration and extent of snow cover in the Snowy Mountains and a comparison with Switzerland. *Search,* 15: 327–331.

Spencer, A. W., 1984: Food habits, grazing activities, and reproductive development of long-tailed voles, *Microtus longicaudus* (Merram) in relation to snow cover in the mountains of Colorado. *In* Merritt, J. F. (ed.), *Winter ecology of small mammals.* Pittsburgh: Carnegie Museum of Natural History, Special publication no. 10, 67–90.

Stenseth, N. C., Shabarr, A., Chan, K. S., Boutin, S., Rueness, E. K., Ehrich, D., Hurrell, J. W., Lindjaerde, O. C., and Jakobsen, K. S., 2004: Snow conditions may create an invisible barrier for lynx. *Proceedings of the National Academy of Sciences of the United States of America,* 101: 10632–10634.

Sturm, M., Holmgren, J., and Liston, G. E., 1995: A seasonal snow cover classification system for local to global applications. *Journal of Climate,* 8: 1261–1283.

Whetton, P., 1998: Climate change impacts on the spatial extent of snow-cover in the Australian Alps. *In* Green, K. (ed.), *Snow: a natural history; an uncertain future.* Canberra: Australian Alps Liaison Committee, 195–206.

Whetton, P. H., Halock, M. R., and Galloway, R. W., 1996: Climate change and snow cover duration in the Australian Alps. *Climate Change,* 32: 447–479.

Ms accepted December 2005