The impact of climate change on snow conditions in mainland Australia

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CSIRO

CRES

August 2003

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Published by CSIRO Atmospheric Research, Aspendale, Victoria, Australia.

A report for the Victorian Department of Sustainability and Environment, Victorian Greenhouse Office, Parks Victoria, New South Wales National Parks and Wildlife Service, New South Wales Department of Infrastructure, Planning and Natural Resources, Australian Greenhouse Office and Australian Ski Areas Association.

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Executive Summary

The primary aim of this study was to improve the current understanding of the impacts of past and future climate change on natural snow cover in Australia. A secondary aim was to assess the role of snow-making in countering projected changes in snow conditions.

Past changes in natural snow cover

Trends in alpine temperature, precipitation and snow depth were analysed over regions or sites for which data were available. Alpine temperature data at four sites over the past 35 years revealed that warming trends are slightly greater at higher elevations. Alpine precipitation data for the past 50 years showed evidence of small increases in New South Wales, and small decreases in Victoria. Snow depth data from four alpine sites from 1957-2002 indicated a weak decline in maximum snow depths at three sites. A moderate decline in mid-late season snow depths (August-September) was evident at three sites. This may reflect the tendency for mid-late season snow depth to be driven by ablation (melt and evaporation) while early season snow depth is precipitation driven.

Future changes in natural snow cover

Simulations of future snow conditions in the Australian alpine regions were prepared for the years 2020 and 2050, based on climate change projections published by CSIRO in 2001. A new climate-driven snow model was developed and applied to this study.

The results for 2020 are of greatest relevance to future management of both ski resorts and sites of biological significance due to the much smaller range of uncertainty associated with the projected changes in temperature and precipitation. Information for 2050 provides some indication of the future but is associated with a far greater range of uncertainty.

Two scenarios were used in the model, both of which were equally likely, but associated with uncertainties. The low impact scenario used the lowest projected warming combined with the highest estimate of increased precipitation. The high impact scenario used the highest projected warming with the highest estimate of decreased precipitation. We have very high (at least 95%) confidence that the low impact limits will be exceeded and that the high impact limits will not be exceeded.

Under the low impact and the high impact scenarios respectively, the total alpine area with an average of at least one day of snow cover decreases 10-39% by 2020, and 22-85% by 2050. The area with at least 30 days of snow cover decreases 14-54% by 2020, and 30-93% by 2050. The area with at least 60 days of cover shrinks 18-60% by 2020, and 38-96% by 2050.

At all sites, the low impact scenario for 2020 only has a minor impact on snow conditions. Average season lengths are reduced by around five days. Reductions in peak depths are usually less than 10%, but can be larger at low sites (e.g. Mt Baw Baw and Wellington High Plains). The high impact scenario for 2020 leads to reductions of 30-40 days in average season lengths. At higher sites such as Mt Hotham, this can represent reductions in season duration of about 25%, but at lower sites such as Mt Baw Baw the reduction can be more significant (up to 60%). Impacts on peak depth follow a similar pattern: moderate impacts at higher elevation sites, large impacts at lower elevation sites. There is also a tendency for the time of maximum snow depth to occur earlier in the season under warmer conditions. For example, the results for Thredbo show this occurring about 20 days earlier under the high impact scenario.

Future requirements for snow-making by 2020

Snow-making at ski resorts will be one of the major ways of adapting to greenhouse warming. We assessed the effect of warmer conditions on the number of hours suitable for snow-making by 2020, and the Potential Volume of snow that could be made using two types of snow-guns (Brand A and Brand B, names withheld for commercial reasons) at each resort. The average number of hours suitable for snow-making declines by 2-7% for the low impact scenario and by 17-54% for the high impact scenario. The potential snow-making volume is reduced by 3-10% under the low impact scenario, and by 18-55% under the high impact scenario.

Based on target snow-depth profiles for May to September nominated by snow-making managers at each resort, the snow model was able to simulate the amount of man-made snow required, taking into account natural snowfall, snow-melt and the pre-existing natural snow depth. We computed the Target Volume of man-made snow required over a typical ski run at each resort to achieve the target profile in 90% of years.

Using information about the Potential Volumes of snow that could be made, the number of snow-guns needed to achieve the Target Volumes was estimated, under present and 2020 conditions. The results are significantly influenced by the elevations at which snow-making hours were computed, i.e. 1340 metres at Lake Mountain and Mt Thredbo, 1460 metres at Mt Baw Baw, 1550 metres at Mt Selwyn, 1642 metres at Falls Creek and 1720 metres at Mt Buller and Mt Perisher. About one Brand A gun per ski run is needed at Mt Perisher under present conditions, 1.8 at Falls Creek, almost three at Mt Selwyn and Mt Buller, and 15 at Lake Mountain. An increase of 11-24% in the number of Brand A snow-guns would be required for the low impact scenario, and 73-200% for the high impact scenario. Brand B snow-guns produce slightly less snow than Brand A. Under present conditions, about one Brand B gun per ski run is needed at Mt Perisher, 2.6 at Falls Creek and Mt Thredbo, 4.2 at Mt Selwyn and Mt Buller, and 21 at Lake Mountain. An increase of 11-27% in the number of these snow-guns would be required for the low impact scenario, and 71-188% for the high impact scenario. Therefore, with sufficient investment in snow-guns, the Australian ski industry will be able to manage the impact of projected climate change on snow cover until at least 2020, bearing in mind the limitations outlined below.

This study required some simplifying assumptions (e.g. only two snow-guns, operated automatically) and exclusion of various factors that were not easily included in our model, i.e:

- likely improvements in snow-making technology;
- continuing improvements in snow-making operations such as:
  - optimized snow-gun start-up temperatures;
  - management of the number of pumps and pressure gradients to minimize water heating;
  - increased efficiency of water cooling systems;
  - snow-plume placement;
  - elevation of snow guns on towers;
  - additives to enhance conversion of water to snow;
  - snow grooming and snow-farming.
- the effect of cold air drainage on snow-making capacity at lower elevations;
- the effect of topographic aspect on natural snow deposition;
- less rapid snow-melt rate for man-made snow relative to natural snow;
- possible water-supply limitations due to projected reductions in precipitation and increased evaporation in south-east Australia;
- acceptable levels of environmental impact, e.g. likely increase in demand for water and energy due to increased snow-making.

Summary

Scope of this report

This assessment of past and future changes in snow conditions was prepared by CSIRO and the Australian National University (ANU) based on completion of the following tasks:

1. Collection and preparation of climate databases;
2. Analysis of databases for trends in alpine conditions;
3. Modification of CSIRO's existing snow model and its application to the estimation of natural snow cover by the years 2020 and 2050;
4. Preliminary assessment of the implications of the findings for future snow-making.

Aims of this study

The primary aim of this study was to improve the current understanding of the impacts of past and future climate change on natural snow cover in Australia.

A secondary aim was to assess the role of snow-making as an adaptive response in countering projected changes in snow conditions.

Past changes in natural snow cover

Trends in alpine temperature, precipitation and snow depth were analysed over regions or sites for which data were available. Alpine temperature data at four sites over the past 35 years revealed that warming trends are slightly greater at higher elevations. Alpine precipitation data for the past 50 years showed evidence of small increases in New South Wales, and small decreases in Victoria. Snow depth data from four alpine sites from 1957-2002 indicated a weak decline in maximum snow depths at three sites. A moderate decline in mid-late season snow depths (August-September) was evident at three sites. This may reflect the tendency for mid-late season snow depth to be driven by ablation (melt and evaporation) while early season snow depth is precipitation driven.

Climate change projections used in this study

The most recent projections for climate change in Australia were released by CSIRO in May 2001. Application of these projections in CSIRO's snow model has provided estimates of changes in snow conditions for 2020 and 2050 under two different scenarios, 'low impact' and 'high impact', with projected changes in temperature and precipitation as described in Table 1S. The low impact scenario used the lowest projected warming combined with the highest estimate of increased precipitation. The high impact scenario used the highest projected warming with the highest estimate of decreased precipitation.

Table 1S: Changes in alpine temperature and precipitation for 2020 and 2050, relative to 1990.

Scenario (Year)	Projected Change in Temperature (°C)	Projected Change in Precipitation (%)
Low impact (2020)	+0.2	+0.9
High Impact (2020)	+1.0	-8.3
Low impact (2050)	+0.6	+2.3
High impact (2050)	+2.9	-24.0

It should be noted that the values within the ranges shown in Table 1S are equally probable. We have very high confidence (at least 95%) that the low impact scenarios for 2020 and 2050 will be exceeded and that the high impact scenarios will not be exceeded.

Relevance of the data to managers of ski resorts and natural resources

Results for 2020 are of greatest relevance to future management of both ski resorts and sites of biological significance due to the smaller range of uncertainty in the projected changes in temperature and precipitation. Projections to 2050 provide an indication of the future but are associated with a far greater range of uncertainty.

Future changes in natural snow cover

A new version of CSIRO's climate-driven snow model was developed and applied to this study. Standard outputs of the snow model are:

- snow depth;
- snow cover duration;
- snow ablation-rate;
- snow-to-rainfall ratio;
- regional maps and site-specific snow-depth profiles;
- probability of snow depth at a given date;
- snow-line elevation.

Simulations of future snow conditions in the Australian alpine regions were prepared for the years 2020 and 2050, based on climate change projections published by CSIRO in 2001, applied to the new snow model.

Under the low impact and the high impact scenarios respectively, the total alpine area with an average of at least one day of snow cover decreases 10-39% by 2020, and 22-85% by 2050. The area with at least 30 days of snow cover decreases 14-54% by 2020, and 30-93% by 2050. The area with at least 60 days of cover shrinks 18-60% by 2020, and 38-96% by 2050.

The low impact scenario for 2020 has a minor impact on snow conditions. Average season lengths are reduced by around five days. Reductions in peak depths are usually less than 10%, but can be larger at lower sites (e.g. Mt Baw Baw and Wellington High Plains). The high impact scenario for 2020 leads to reductions of 30-40 days in average season lengths. At higher sites such as Mt Hotham, this can represent reductions in season duration of about 25% (Figure 1S), but at lower sites such as Mt Baw Baw the reduction can be more significant (up to 60%). Impacts on peak depth follow a similar pattern: moderate impacts at higher elevation sites, large impacts at lower elevation sites. There is also a tendency for the time of maximum snow depth to occur earlier in the season under warmer conditions. For example, the results for Thredbo show this occurring about 20 days earlier under the high impact scenario.

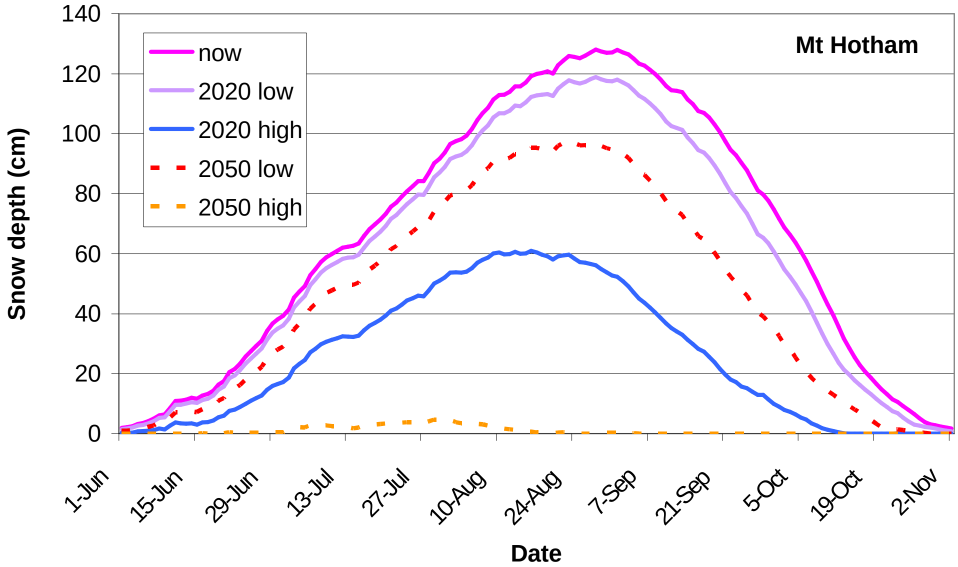

Figure 1S: Simulated 20-year average snow-depth profiles at Mt Hotham (1,882 m) for present (1979-1998), 2020 and 2050.

The snowline is expected to rise with global warming. For example, at Mt Kosciuszko, the snowline elevation on 1 September is predicted to rise from the present average of 1,461 metres to between 1,488 and 1,624 metres by 2020. The probability of exceeding a natural snow depth of 30 cm each day also declines with greenhouse warming. For example, at Mt Hotham on 1 July, the probability drops from the present value of 65% to 15-60% by 2020.

Under the low impact scenario for 2050, season durations are decreased by 15-20 days at most sites. Such reductions are relatively minor at high sites but can represent a substantial impact at low sites. The reductions in peak depths range from around 10% at the highest sites to more than 80% at low sites such as Mt Baw Baw. The high impact scenario for 2050 leads to very large reductions in season duration and peak depth at all sites. Season durations are typically reduced by around 100 days, which leaves only the highest sites with durations of more than ten days. Maximum depths shrink to less than 10% of their present value and occur much earlier in the season.

Future requirements for snow-making by 2020

Adaptation to greenhouse warming will be needed in natural and managed systems. Adaptation strategies for native fauna and flora are beyond the scope of this report but have been discussed in other literature (e.g. Brereton et al., 1995). One of the various adaptation options at ski resorts is increased use of snow-making to maintain adequate snow depths.

We assessed the effect of warmer conditions on the number of hours suitable for snow-making and the Potential Volume of snow that could be made with two types of snow-guns typically used at Australian resorts (brand-names withheld for commercial reasons). Brand A snow-guns produced more snow at each resort than Brand B. The results are significantly influenced by the elevations at which snow-making hours were computed, i.e. 1340 metres at Lake Mountain and Mt Thredbo, 1460 metres at Mt Baw Baw, 1550 metres at Mt Selwyn, 1642 metres at Falls Creek and 1720 metres at Mt Buller and Mt Perisher. On average each year, Mt Perisher could produce about 50,000 cubic metres of snow per Brand A snow-gun. Mt Thredbo, Mt Selwyn, Mt Buller and Falls Creek could produce about 20,000 cubic metres of snow per Brand A snow-gun (Figure 2S), and about 15,000 cubic metres per Brand B snow-gun. Baw Baw could produce about half these amounts, and Lake Mountain could produce about one quarter. For both snow-guns, the average number of hours suitable for snow-making declines by 2-7% for the low impact scenario and by 17-54% for the high impact scenario. The potential snow volumes are reduced by 4-10% under the low impact scenario, and by 27-55% under the high impact scenario.

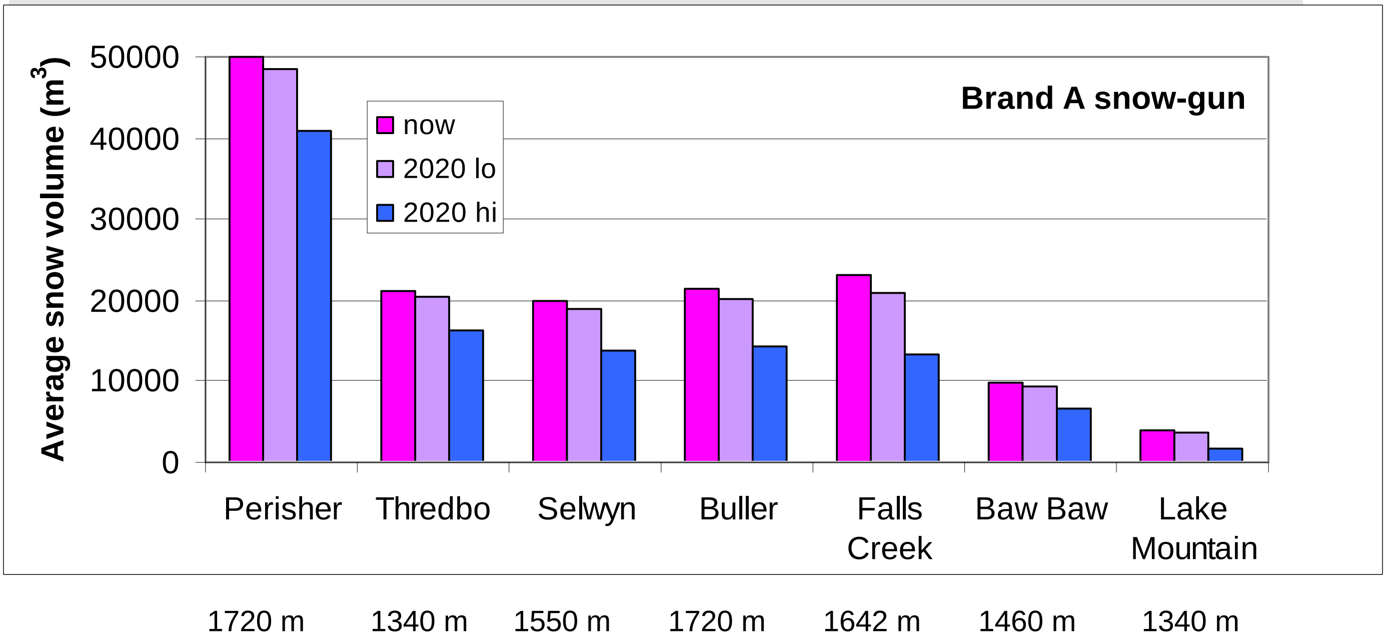

Figure 2S: Average potential volume of snow (cubic metres) that could have been made during May to September by each Brand A snow-gun when wet-bulb temperatures were below -2°C for present and 2020. No wet-bulb temperature data were available for Mt Hotham.

Based on target snow-depth profiles nominated by snow-making managers at each resort (Table 2S), we used the snow model to simulate the amount of man-made snow required, taking into account natural snowfall, snow-melt and the pre-existing natural snow depth. June was the month with greatest need for man-made snow. Using data for 1950 to 1998, we computed the Target Volume of man-made snow required at each resort to achieve the target profile in 90% of Junes over a typical ski run (500 metres long and 40 metres wide).

Table 2S: Target snow-depths (cm) defined by snow-making managers at each ski resort. Results for Mt Hotham and Baw Baw are not shown since monthly wet-bulb temperature data were unavailable. * The target depth at Selwyn and Lake Mountain was set at 0 cm on 15 Sept.

Resort	1 June	30 June	31 July	31 August	30 Sept
Perisher	1	30	60	100	40
Thredbo	1	30	60	100	40
Selwyn	1	20	30	45	0*
Falls Creek	1	30	60	100	40
Mt Buller	1	30	50	90	20
Lake Mountain	1	30	30	30	0*

Using information about the Potential Volumes of snow that could be made, the number of snow-guns needed to achieve the Target Volumes was estimated, under present and 2020 conditions. About one Brand A snow-gun per ski run is needed at Mt Perisher under present conditions, 1.8 at Falls Creek, almost three at Mt Selwyn and Mt Buller, and 15 at Lake Mountain. An increase of 11-24% in the number of Brand A snow-guns would be required for the low impact scenario, and 73-200% for the high impact scenario (Figure 3S). Brand B snow-guns produce slightly less snow than Brand A. Under present conditions, about one Brand B snow-gun per ski run is needed at Mt Perisher, 2.6 at Falls Creek and Mt Thredbo, 4.2 at Mt Selwyn and Mt Buller, and 21 at Lake Mountain. An increase of 11-27% in the number of these snow-guns would be required for the low impact scenario, and 71-188% for the high impact scenario. Therefore, with sufficient investment in snow-guns, the Australian ski industry will be able to manage the impact of projected climate change on snow cover until at least 2020, bearing in mind the limitations outlined below.

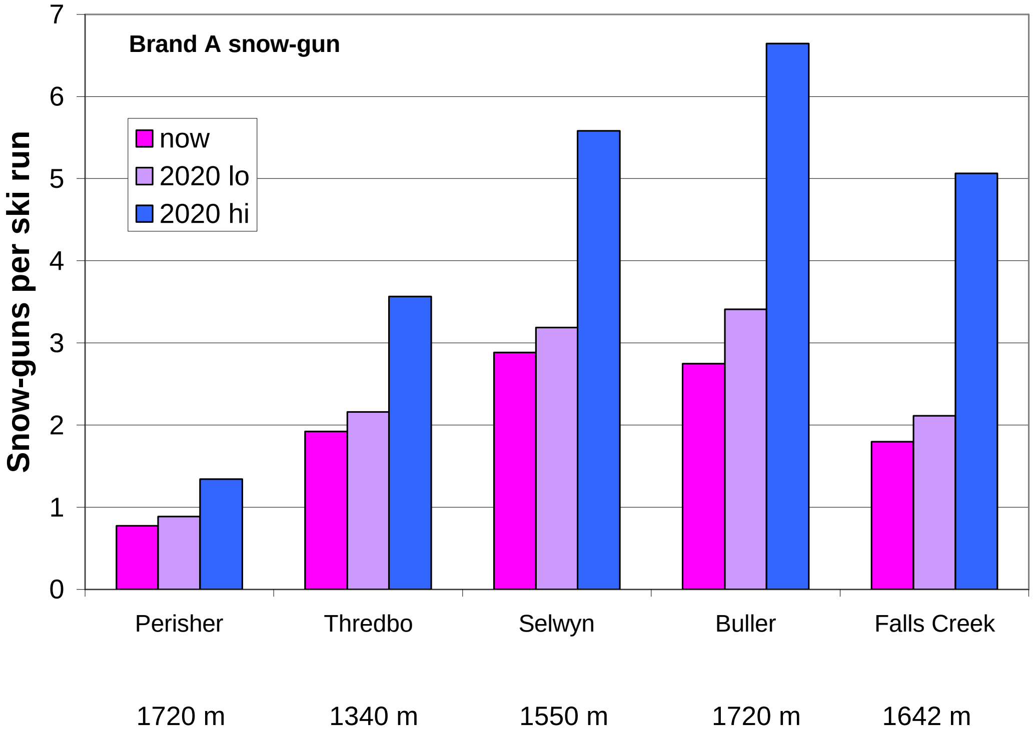

Figure 3S: Number of Brand A snow-guns needed to achieve resort-specific target snow-depth profiles (Table 1S) in 90 % of Junes on a typical ski-run, for present and 2020 conditions.

Limitations of the model in relation to snow making

This study required some simplifying assumptions, whilst excluding a number of physical and management effects that are not easily included in CSIRO's modeling framework. Apart from limiting the results to two types of snow-guns, other physical and management exclusions were:

- likely improvements in snow-making technology;
- continuing improvements in snow-making operations such as:
  - optimized snow-gun start-up temperatures;
  - management of the number of pumps and pressure gradients to minimize water heating;
  - increased efficiency of water cooling systems;
  - snow-plume placement;
  - elevation of snow guns on towers;
  - additives to enhance conversion of water to snow;
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- the effect of cold air drainage on snow-making capacity at lower elevations;
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- less rapid snow-melt rate for man-made snow relative to natural snow;
- possible water-supply limitations due to projected reductions in precipitation and increased evaporation in south-east Australia;
- acceptable levels of environmental impact, e.g. likely increase in demand for water and energy due to increased snow-making.

Introduction

Global warming

Since the Industrial Revolution in the 18th century, human activities have increased the levels of the main greenhouse gases – carbon dioxide, water vapour, methane, nitrous oxide and ozone in the lower atmosphere, and chlorofluorocarbons. The growth of carbon dioxide emissions is derived largely from the burning of fossil fuels and land clearing, results in about half of carbon dioxide remaining in the atmosphere, with the remaining half taken up almost equally between the oceans and vegetation.

The present carbon dioxide concentration is greater than any recorded level for the past 420,000 years. During the past 100 years, the Earth's average temperature has risen by about 0.6°C, with 1998 being the warmest on record, 2002 the second warmest and the 1990s being the warmest decade (WMO, 2002). The Intergovernmental Panel on Climate Change (IPCC) has concluded that "an increasing body of observations gives a collective picture of a warming world and other changes in the climate system". The other changes include a 10 to 20 cm rise in global-average sea-level since 1900, warming of the deep ocean and the lowest 8 km of the atmosphere, and a reduction in snow cover and the area of sea-ice.

Australia's alpine regions and climate change

Greenhouse warming has the potential to reduce snow cover in the Australian Alps (Figure 1), however the large annual variability in snow season characteristics at various locations makes it difficult to detect trends. Traditionally, data have been collected from a small number of alpine sites and analysed statistically to estimate trends.

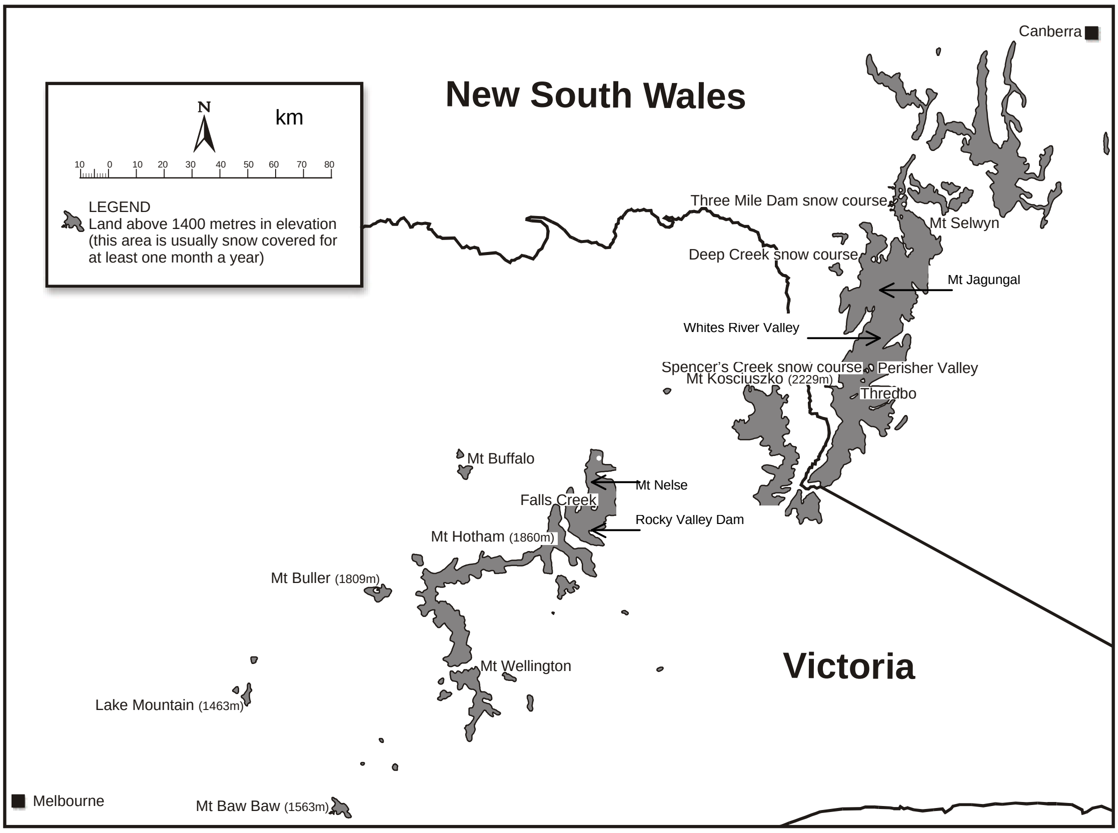

Figure 1: Study region and alpine sites referred to in this report. From Ruddell et al. (1990).

Ruddell et al. (1990) showed that snow depths had declined at some sites from the 1950s to 1989, but no trends were statistically significant the 90% confidence level. Given that most of south-eastern Australia has continued to warm over the past decade, an updated assessment of snow trends is needed to show whether there has been any change in the rate of decline, and whether these trends are consistent with projections based on greenhouse warming. This has been assessed in the current study.

The most recent projections of natural snow cover taking into account greenhouse warming were published by Whetton (1998), based upon CSIRO's (1996) climate change scenarios and CSIRO's snow model (Whetton et al. 1996). Since 1998, CSIRO has released new Australian climate change projections (May 2001) and the snow model has been modified to give a broader range of outputs and more reliable projections of natural snow (See Appendix 1).

The current study updates information on observed changes in climate and snow in the Australian Alps since 1950. It also brings together the improved snow model and updated climate projections (CSIRO, 2001) to estimate potential changes in natural snow cover and depth by 2020 and 2050. An assessment is made of the ability for ski resorts to adapt through increased snow-making.

Analysis of alpine climate trends since the mid-1950s

The databases and methods used to assess alpine climate trends are described in Appendix 1. Changes in maximum and minimum temperature, precipitation and natural snow depth since the 1950s are outlined below.

Temperature changes

Australia has warmed by 0.7^{o}C since 1910, with most of the warming occurring since 1950. Grided data from the Bureau of Meteorology from 1950 to 2001 (Figure 2) show an increase in winter maximum temperature in south-east Australia with little change in minimum temperature. However, Cabrumurra was the only alpine site included in this grided dataset.

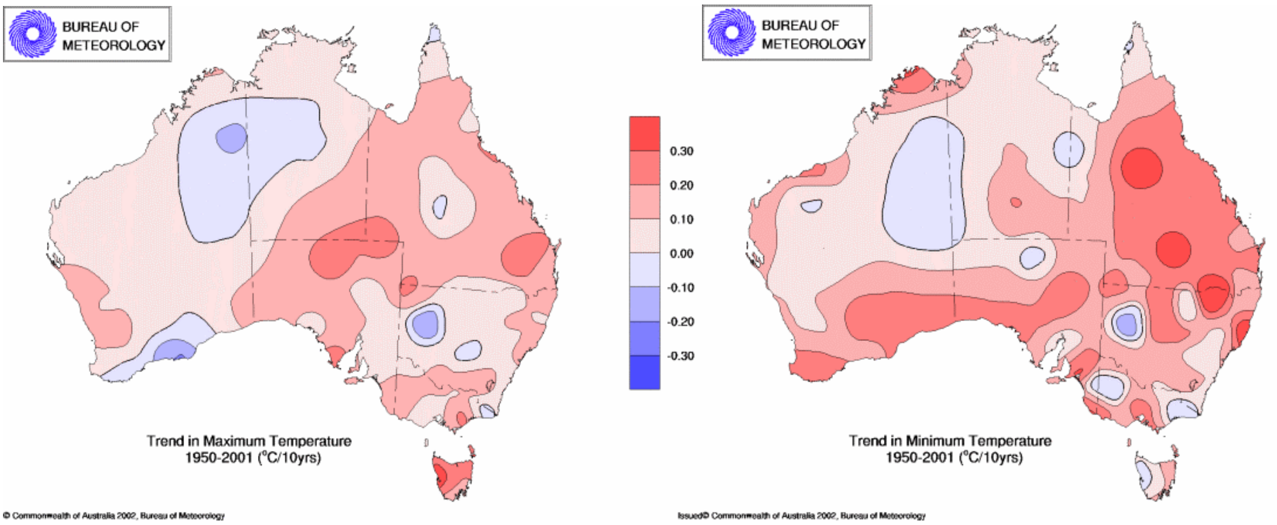

Figure 2: Trends in winter maximum (left) and minimum (right) temperature (°C/decade) from 1950 to 2001, based on Bureau of Meteorology Reference Climate Stations.

In the current study, temperature data were analysed at eight high altitude sites in south-east Australia for which reliable temperature data were available, four of which were above 1,300 metres. Trends in minimum and maximum temperatures from June to September were calculated over various periods between 1962 and 2001 (Table 1). Positive trends were evident in most months at Cabramurra, Perisher Valley, Thredbo Automatic Weather Station (AWS) and Thredbo Village (Figures 3 and 4), especially for July and September. The alpine trends over approximately 35 years were close to +0.02^{o}C per year. At sites below 1,000 metres, trends were weak and inconsistent.

Table 1: Maximum and minimum temperature trends averaged over June to September at four sites above 1,300 metres elevation.

Site	Elevation (m)	Period (years)	T_{max} trend ^{o}C/yr	T_{min} trend ^{o}C/yr
Cabrumurra	1,480	1962-1998	+0.023	+0.004
Perisher	1,735	1976-2001	+0.057	+0.034
Thredbo AWS	1,957	1967-2001	+0.020	+0.021
Thredbo Village	1,380	1967-2001	+0.035	+0.031

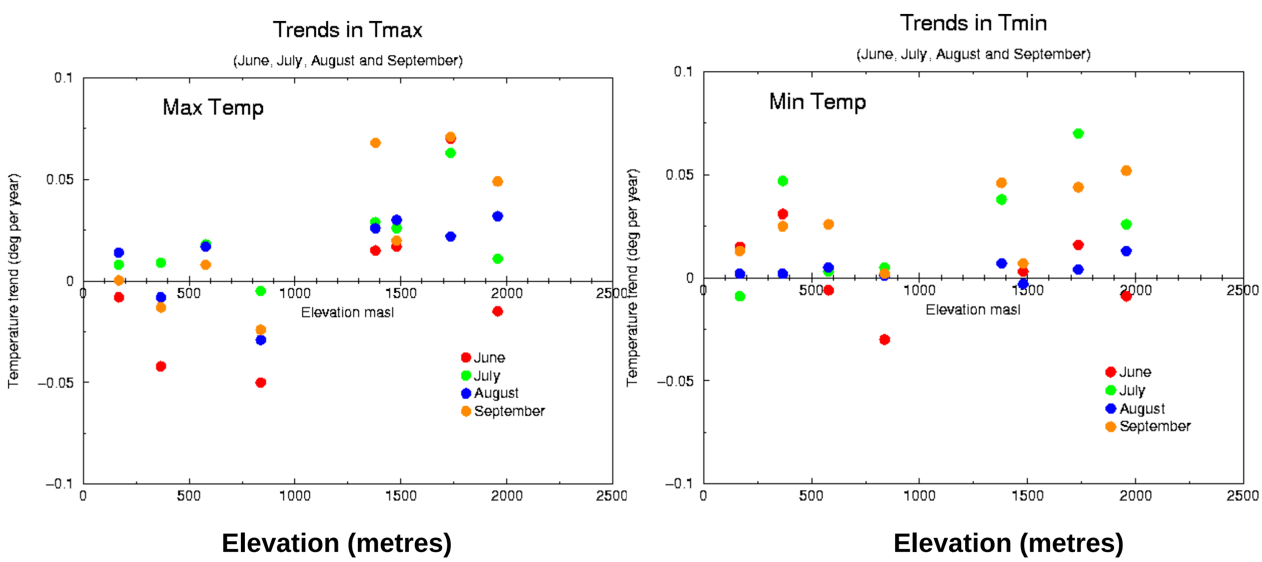

Figure 3: Trends for June, July, August and September maximum and minimum temperatures at eight sites in south-east Australia for various periods between 1962 and 2001 (see Table 1). From left to right in each panel, the stations are Rutherglen, Mt Beauty, Canberra, Rubicon, Thredbo Village, Cabrumurra, Perisher and Thredbo Automatic Weather Station (AWS).

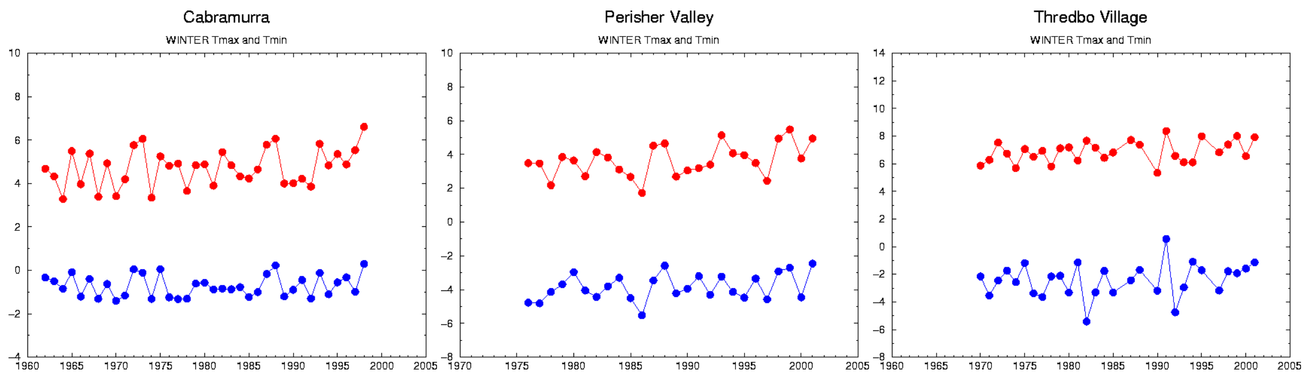

Figure 4: Time series of winter (June-Aug) maximum (red) and minimum (blue) temperature (°C) at three alpine sites.

Precipitation changes

Annual average precipitation has decreased over most of eastern Australia and south-western Australia, and increased over north-western Australia since 1950. The grided precipitation data from the Bureau of Meteorology for 1950 to 2001 (Figure 5) show a decrease over the southern Alps and an increase over the northern Alps. Although these results are based on interpolation of data from non-alpine sites, they were confirmed using the finer resolution ANU CRES grided precipitation data that include some alpine sites (Figure 6). For June to September between 1951 and 2000, small changes in alpine precipitation tended toward increases in the New South Wales Alps and decreases in the Victorian Alps, consistent with the lower than average rainfall seen in southern parts of Victoria over the past seven years.

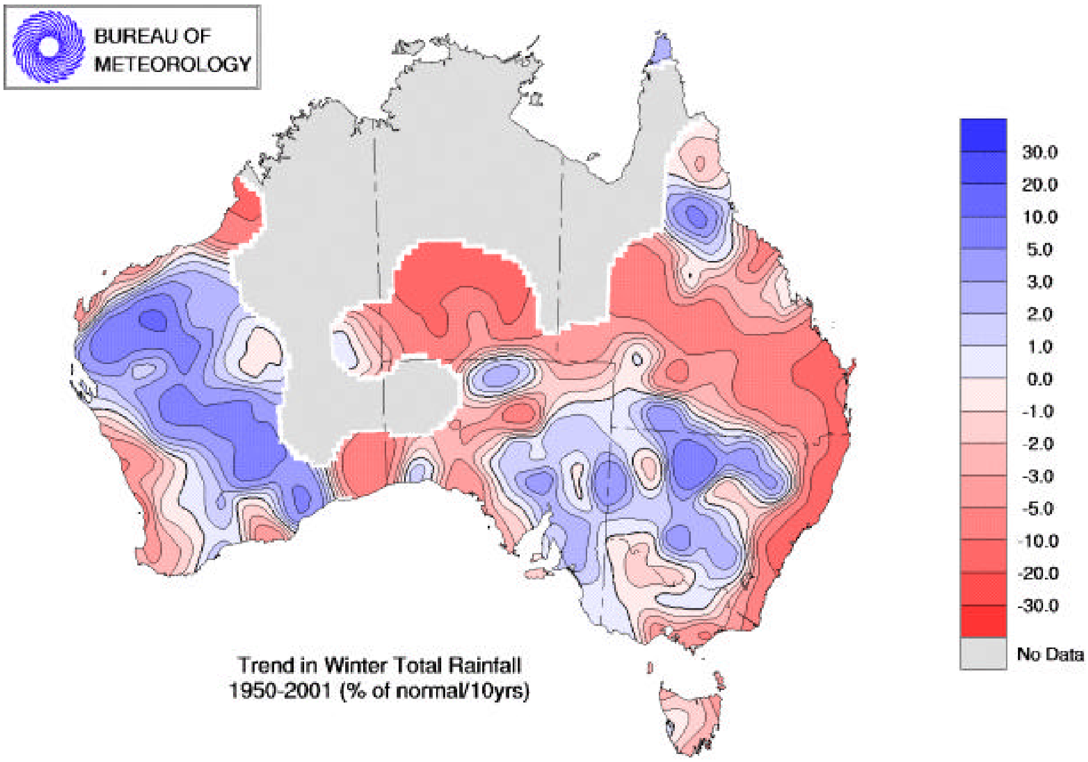

Figure 5: Trends in winter precipitation (% / decade) from 1950-2001, based on Bureau of Meteorology Reference Climate Stations. The "normal" reference period is 1961-1990.

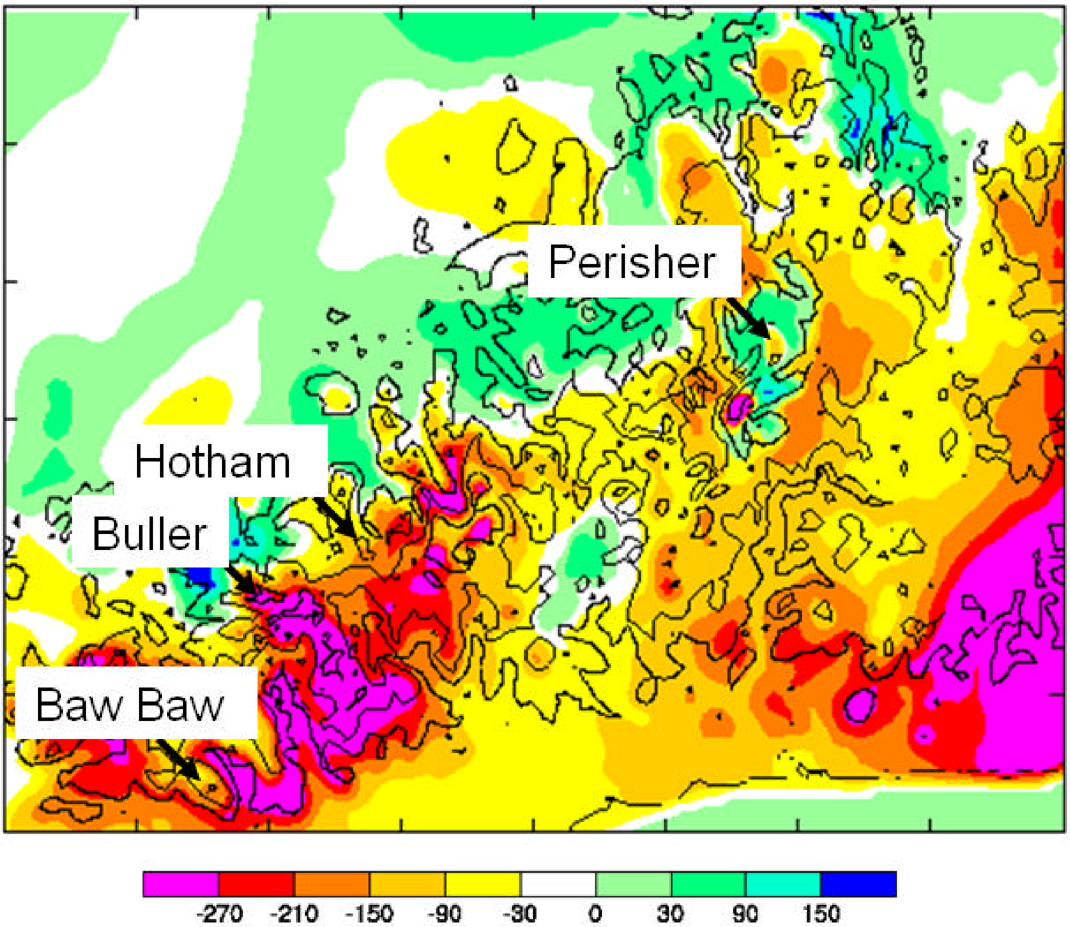

Figure 6: Trends in June to September precipitation (mm / century) from 1951 to 2000, based on the ANU CRES interpolation of data from the Bureau of Meteorology.

Changes in depth of natural snow

Analysis of maximum snow depth data from 1957 to 2002 at Deep Creek (NSW), Three Mile Dam (NSW), Rocky Valley Dam (Vic) and Spencers Creek (NSW) gave trends of +0.09, -0.07, -0.33 and –0.43 cm/year, respectively (Figure 7). These trends represented percentage changes per decade of +0.7, -1.3, -2.8 and –2.2 respectively. None of the trends was statistically significant at the 90% confidence level.

To compare these results with those of Ruddell et al. (1990), we needed to convert snow depth data to water equivalent data using an average snow-density factor of 0.4. Table 2 shows that the decline in maximum snow depth has slowed in the 1990s at Three Mile Dam, Rocky Valley Dam and Spencers Creek, and reversed at Deep Creek.

Slater (1995) estimated that snow depth had declined 25% at Spencers Creek between 1954 and 1993. Davis (1998) found a decrease in the number of Snowy Mountain snow-days from 1970 to 1996, particularly in May and August and Green (2000) noted a decreasing trend in integrated weekly snow depth at Spencers Creek from 1959 to 1999.

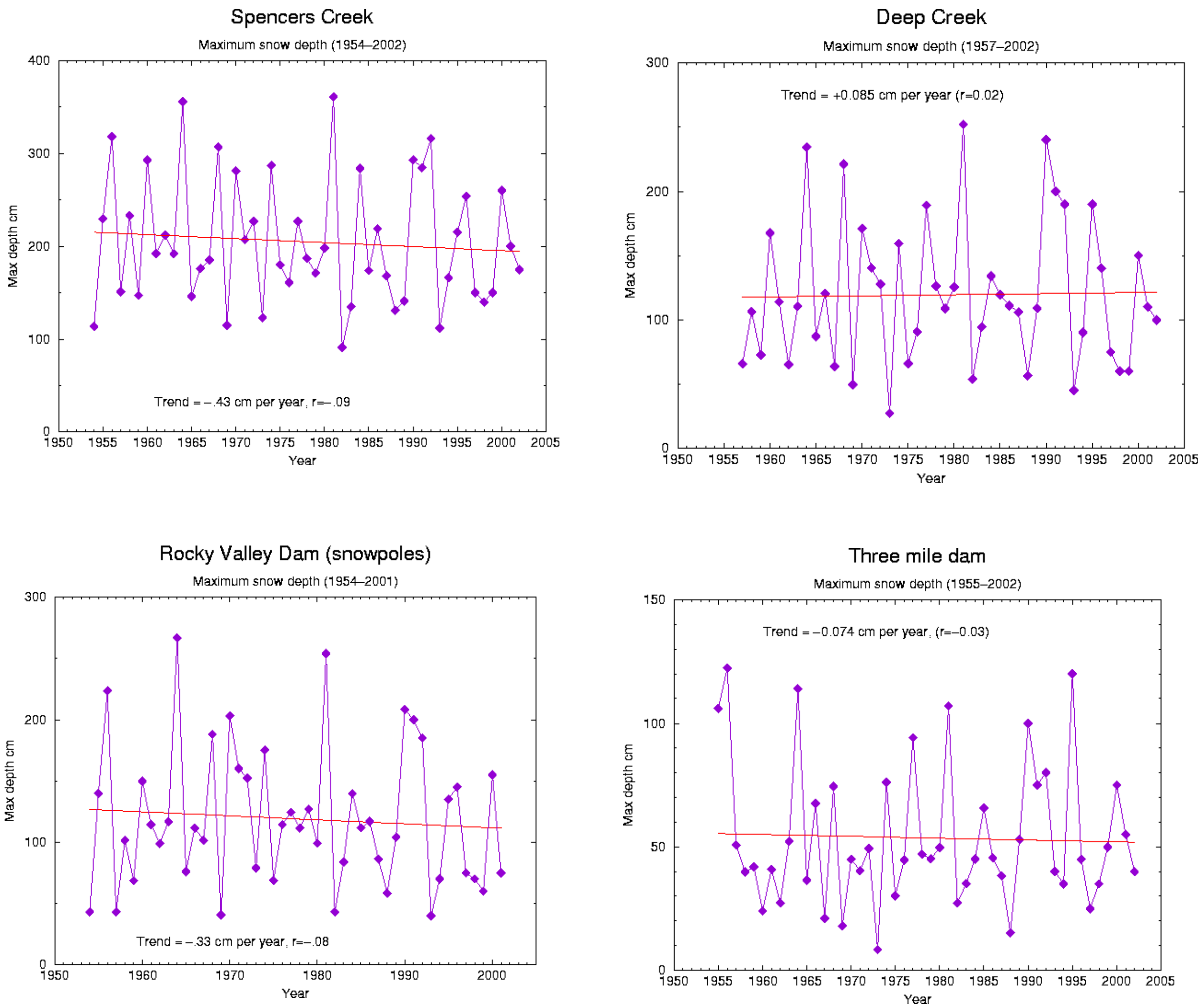

Figure 7: Maximum snow depth (cm) at Spencers Creek (1,830 m), Deep Creek (1,620 m), Rocky Valley Dam (1,650 m) and Three-Mile Dam (1,460 m).

Table 2: Trends in water-equivalent maximum snow depth (cm/yr and %/decade) at Deep Creek, Spencers Creek, Three-Mile Dam and Rocky Valley Dam.

Site	1957-1989[1]	1957-1989[1]	1957-2002	1957-2002
	cm/yr	%/decade	cm/yr	%/decade
Deep Creek	-0.05	-1.00	+0.04	+0.70
3 Mile Dam	-0.05	-2.90	-0.03	-1.30
Rocky Valley Dam	-0.54	-11.10	-0.13	-2.80
Spencers Creek	-0.68	-7.40	-0.17	-2.20

[1]Values for 1957-1989 taken from Ruddell et al. (1990).

Because maximum snow depth usually occurs during late August, trends in maximum snow depth may not be the best indicator of changes in the snow profile at other times of the year, nor of the length of the season. Since the mid-1950s, trends in snow depth on 1 July, 1 August and 1 September at Spencers Creek, Three Mile Dam and Deep Creek showed a decline from August to September (Table 3 and Figure 8). Daily data for Rocky Valley Dam were unavailable. The August 1 decrease was 0.56 to 0.91 cm/year, while the September 1 decrease was 0.27 to 0.46 cm/year.

Table 3: Trends in snow depth (cm/yr) on 1 July, 1 August and 1 September at Deep Creek, Spencers Creek and Three-Mile Dam. Daily data for Rocky Valley Dam were unavailable.

Site	Elevation (m)	Period (years)	1 July	1 Aug	1 Sept
Spencers Creek	1,830	1954-2002	-0.43	-0.91	-0.46
Deep Creek	1,620	1957-2002	+0.56	-0.56	-0.27
Three Mile Dam	1,460	1955-2002	+0.03	-0.57*	-0.26

* significant at the 97% confidence level.

In summary, warming trends at four alpine sites over the past 35 years are greater than the trends assessed at lower elevations. Over the past 50 years, there is evidence of small increases in New South Wales alpine precipitation and small decreases in Victorian alpine precipitation. A small decline in maximum snow depths is evident at three of the four alpine sites in the years between 1957 and 2002. A moderate decline in August and September snow depths is evident at three sites, possibly indicative of the tendency for mid to late season snow depth to be determined by temperature-dependent ablation (melt and evaporation), whereas the depth of early season snow is determined by precipitation.

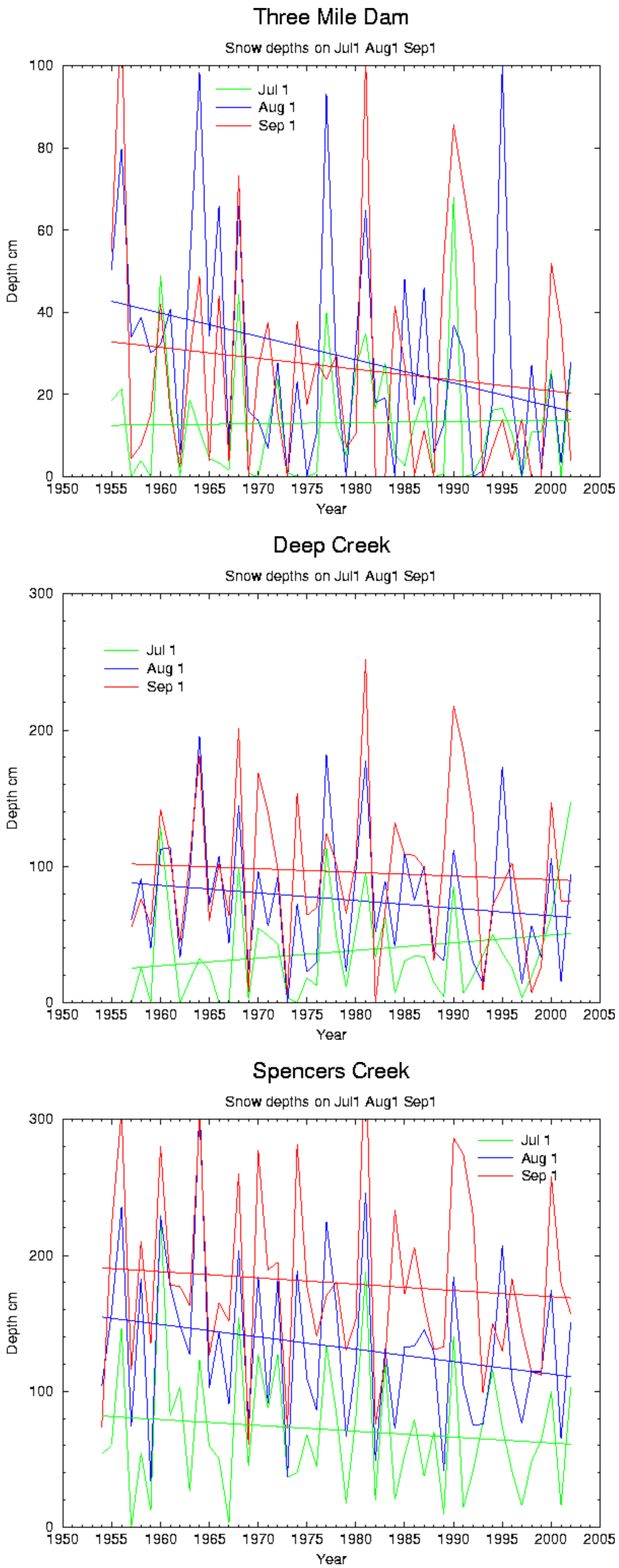

Figure 8: Snow depth (cm) on 1 July, 1 August and 1 September at Spencers Creek (1,830 m), Deep Creek (1,620 m) and Three Mile Dam (1,460 m).

Projected changes in natural snow conditions

Whetton (1998) estimated that the total area with snow cover for at least 30 days in south-east Australia would decline by 18 to 66% by 2030 and by 39 to 96% by 2070. This was based on the 1994 version of CSIRO's snow model and the 1996 version of CSIRO's climate change projections for the alpine region (a warming of 0.3 to 1.3^{o}C and a precipitation change of between 0 and -8% by 2030, and a warming of 0.6 to 3.4^{o}C and a precipitation change of between 0 and -20% by 2070). Since the snow model and climate change projections have been updated, a new assessment of projected impacts on natural snow conditions was needed.

CSIRO climate change projections for the Australian Alps in 2020 and 2050

The IPCC (2001) provided estimates of global warming for the 21st century (Appendix 2). Each of the IPCC climate models gave a unique climate response for a given increase in greenhouse gases – some models have a greater global warming than others. To estimate climate change in the Australian alpine region, model results were compared by expressing the *regional* climate responses as a change per ^{o}C of *global*-average warming. To estimate *regional* changes in temperature and precipitation for 2020 and 2050, the regional changes per ^{o}C of global warming were multiplied by global warming values for 2020 and 2050 (Figure 2-A2 in Appendix 2). Alpine climate change projections are shown in Table 4. For snow, the low impact scenario is the combination of the lowest warming and the greatest precipitation increase, while the high impact scenario is the highest warming combined with the greatest precipitation decrease. We have very high confidence (at least 95%) that the low impact scenarios will be exceeded and the high impact scenarios will not be exceeded. Values within the ranges shown in Table 4 are equally probable.

Table 4: Changes in alpine temperature and precipitation for 2020 and 2050, relative to 1990.

Scenario (Year)	Projected Change in Temperature (°C)	Projected Change in Precipitation (%)
Low impact (2020)	+0.2	+0.9
High Impact (2020)	+1.0	–8.3
Low impact (2050)	+0.6	+2.3
High impact (2050)	+2.9	–24.0

Simulated natural snow depth and duration

An improved version of the snow model (Appendix 1) has been used with the climate change projections in Table 4. Simulated regional patterns of maximum snow depth and snow-cover duration are shown in Figures 9 and 10, respectively, for the present, 2020 and 2050. The total area with an average of at least 1 day of snow cover decreases 10-39% by 2020, and 22-85% by 2050 (Table 5). The area with at least 30 days of snow cover decreases 14-54% by 2020, and 30-93% by 2050. The area with at least 60 days of cover decreases 18-60% by 2020, and 38-96% by 2050.

Table 5: Percentage change in area with at least 1, 30 or 60 days simulated annual-average snow-cover duration for 2020 and 2050, relative to 1990.

Snow duration	2020 low[a]	2020 high[b]	2050 low[a]	2050 high[b]
At least 1 day	–9.9	–39.3	–22.0	–84.7
At least 30 days	–14.4	–54.4	–29.6	–93.2
At least 60 days	–17.5	–60.3	–38.1	–96.3

[a]low impact scenario, [b]high impact scenario

Site-specific results have been calculated for the alpine resorts, each of which has significant biological attributes such as populations of the Mountain Pygmy-possum and Alpine She-oak Skink, as well as alpine snow-patch communities. These resorts are:

- Mt Baw Baw (Victoria);
- Lake Mountain (Victoria);
- Mt Buller (Victoria);
- Mt Buffalo (Victoria);
- Falls Creek (Victoria);
- Mt Hotham (Victoria);
- Mt Thredbo (New South Wales);
- Mt Perisher (New South Wales);
- Mt Selwyn (New South Wales).

The distribution of flora and fauna is expected to change under greenhouse climate effects at the sub-continental level (Brereton et al. 1995) and in the Alps (Green and Pickering, 2002). Snow conditions, depth and snowline can have important implications for the distribution and persistence of biodiversity in the alpine area, so identification of potential changes in conditions can inform future management.

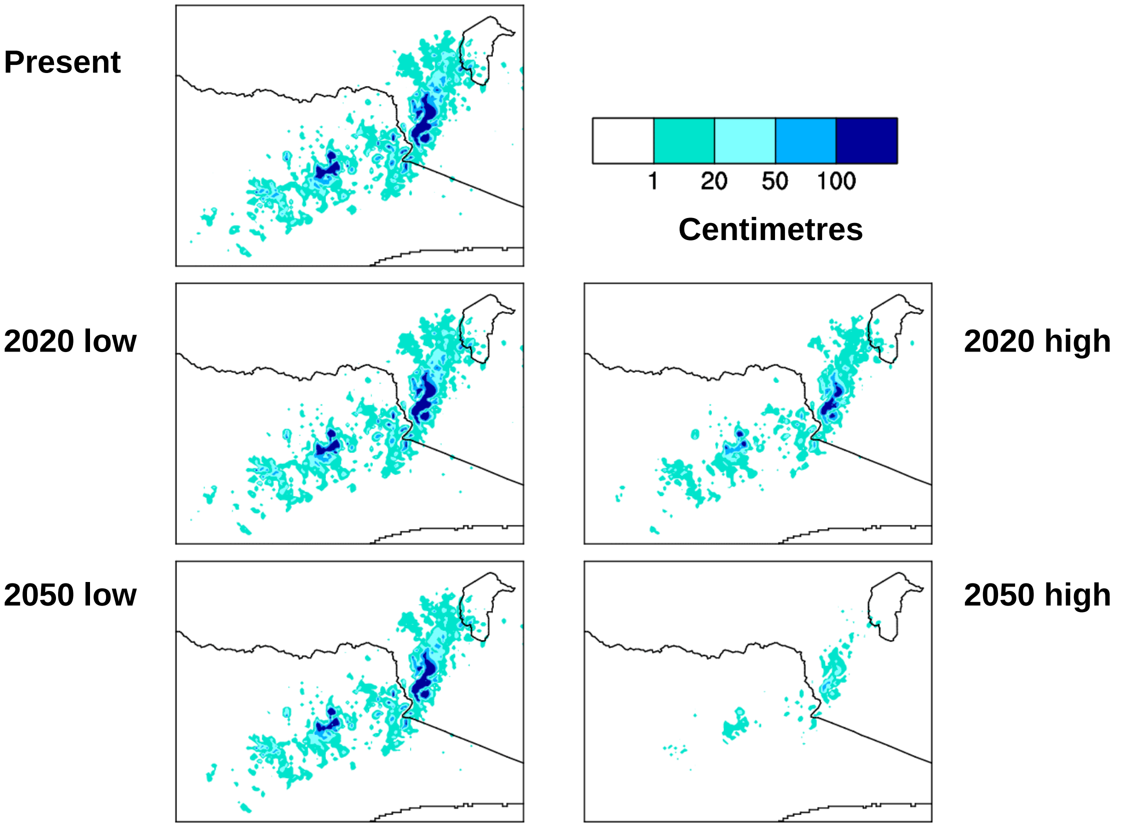

Figure 9: Simulated maximum snow depth (cm) for present, 2020 and 2050.

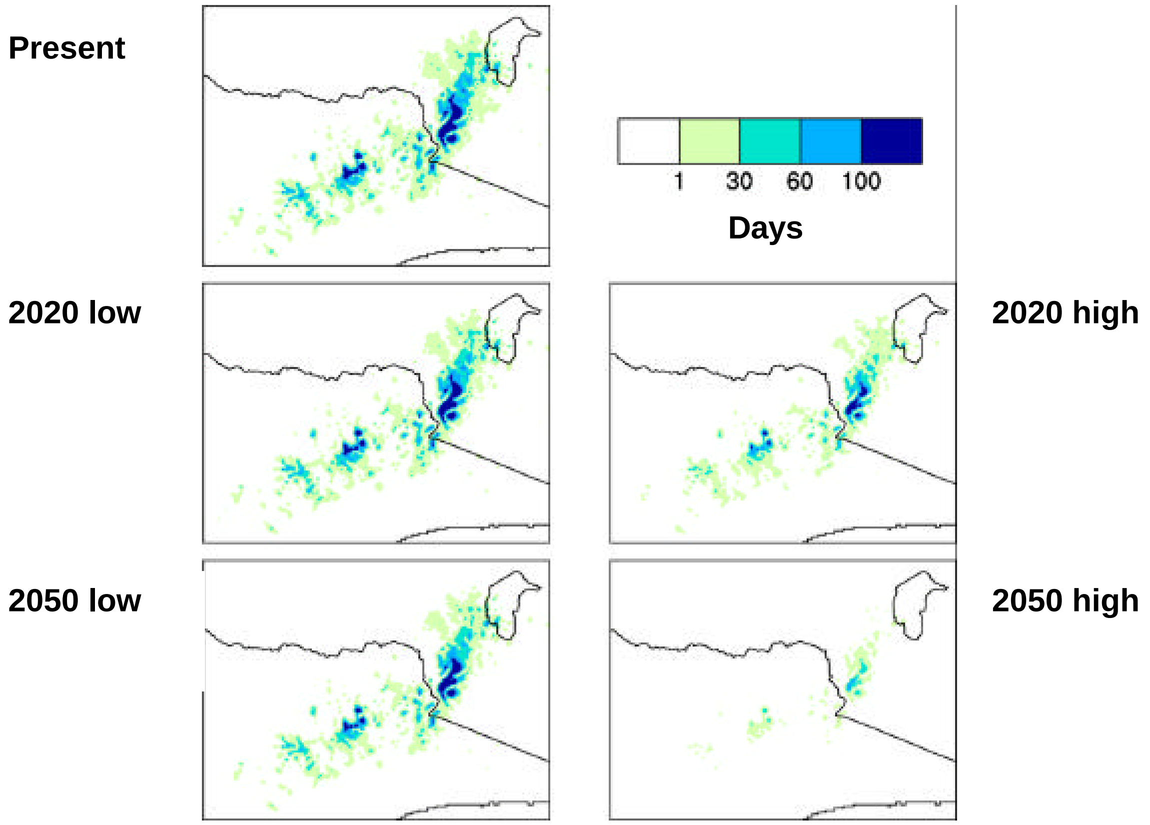

Figure 10: Simulated snow-cover duration (days) for present, 2020 and 2050.

To augment the ecological value of the datasets, five additional non-resort areas were selected to provide site specific data on:

- a broader geographical range across the alps (e.g. Mt Kosciuszko, Wellington High Plains);
- specific biological attributes or ecological processes (e.g. Long Plain-Jagungal - tree line inversion, Mt Nelse - snowpatch);
- sites of scientific interest for which limited data were already available and amenable to longer term monitoring.

The additional five sites were:

- Wellington high plains (Victoria);
- Mt Nelse (Victoria);
- Whites River valley (New South Wales);
- Mt Jagungal (New South Wales);
- Mt Kosciuszko (New South Wales).

Figures 11 to 24 present the snow depth profiles averaged over 20 years for the various alpine sites. Profiles for present conditions were averaged over the period from 1979 to 1998 and profiles for the future were created using climate data from the same 20 years modified by the climate change scenarios. Table 6 shows average duration of snow cover at all sites.

Results for 2020 are of greatest relevance to future management of both ski resorts and sites of biological significance due to the smaller range of uncertainty in the projected changes in temperature and precipitation. Projections to 2050 remain useful as an indication of the future but are associated with a far greater range of uncertainty.

The low impact scenario for 2020 has a minor impact on snow conditions. Average season lengths are reduced by around five days. Reductions in peak depths are usually less than 10%, but can be larger at lower sites (e.g. Mt Baw Baw and Wellington High Plains). The high impact scenario for 2020 leads to reductions of 30-40 days in average season lengths, with smaller impacts at higher elevations and larger impacts at lower elevations. For example, at higher sites such as Mt Hotham, this can represent reductions in season duration of about 25%, but at lower sites such as Mt Selwyn the reduction can be more significant (up to 60%). Impacts on peak depth follow a similar pattern: moderate impacts at higher elevation sites, large impacts at lower elevation sites. There is also a tendency for the time of maximum snow depth to occur earlier in the season under warmer conditions. For example, the results for Mt Thredbo show this occurring about 20 days earlier under the high impact scenario. There is also a tendency for depth reductions to be larger in the late season than in the early season. This pattern is consistent with observed trends.

Under the low impact scenario for 2050, season durations are decreased by 15-20 days at most sites. Such reductions are relatively minor at high sites but can represent a substantial impact at low sites. The reductions in peak depths range from around 10% at the highest sites to more than 80% at low sites such as Mt Baw Baw. The high impact scenario for 2050 leads to very large reductions in season duration and peak depth at all sites. Season durations are typically reduced by around 100 days, which leaves only the highest sites with durations of more than ten days. Maximum depths shrink to less than 10% of their present value and occur much earlier in the season.

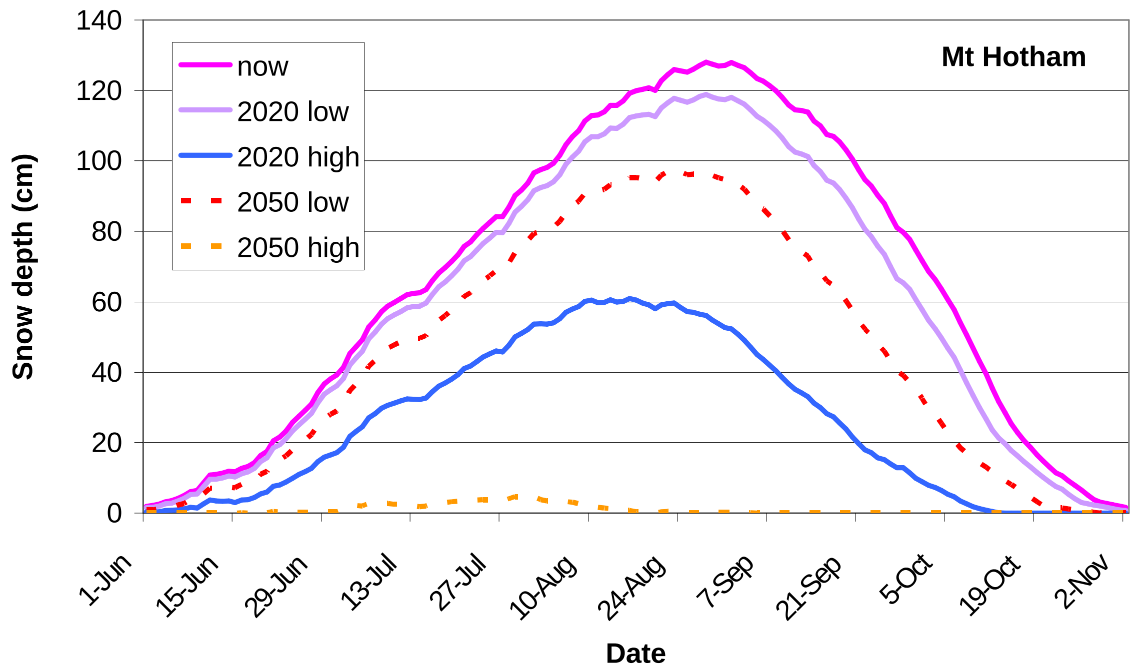

Figure 11: Simulated 20-year average snow-depth profiles at Mt Hotham (1,882 m) for present (1979-1998), 2020 and 2050.

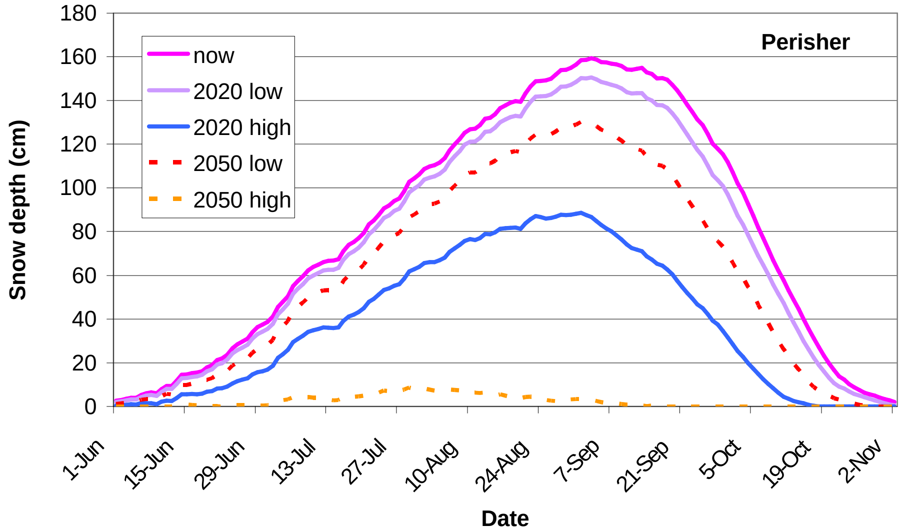

Figure 12: Simulated 20-year average snow-depth profiles at Mt Perisher (1,835 m) for present (1979-1998), 2020 and 2050.

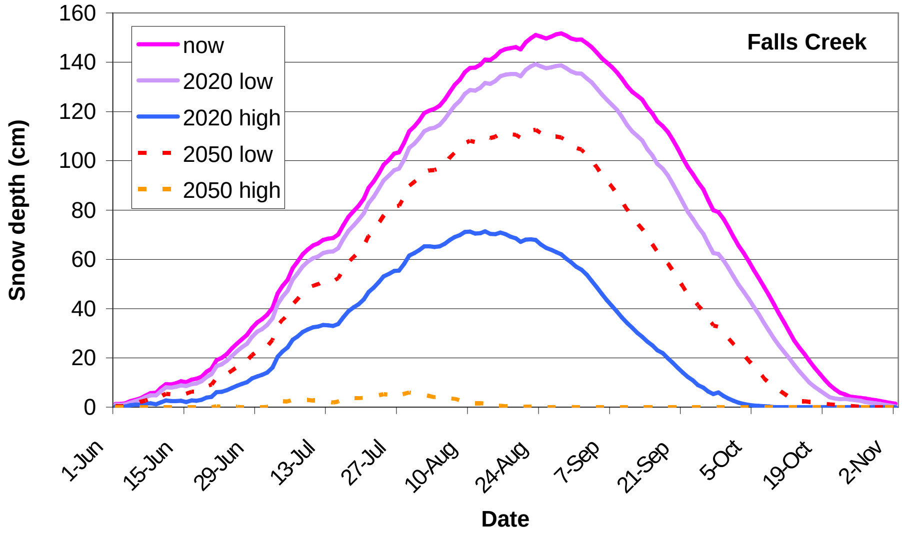

Figure 13: Simulated 20-year average snow-depth profiles at Falls Creek (1,797 m) for present (1979-1998), 2020 and 2050.

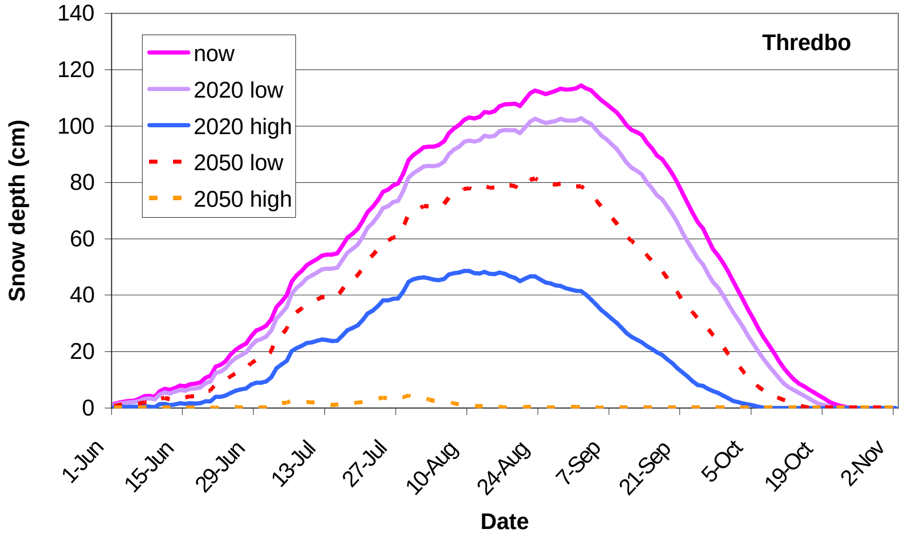

Figure 14: Simulated 20-year average snow-depth profiles at Mt Thredbo (1,715 m) for present (1979-1998), 2020 and 2050.

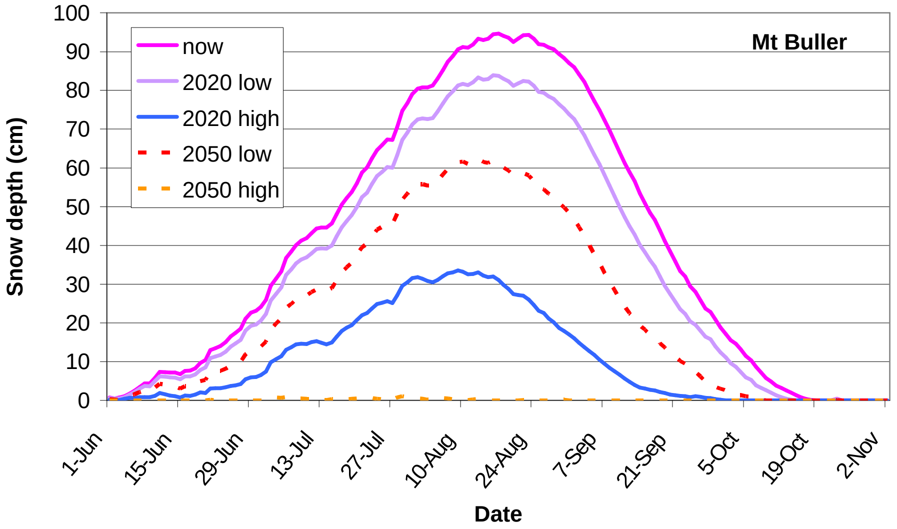

Figure 15: Simulated 20-year average snow-depth profiles at Mt Buller (1,740 m) for present (1979-1998), 2020 and 2050.

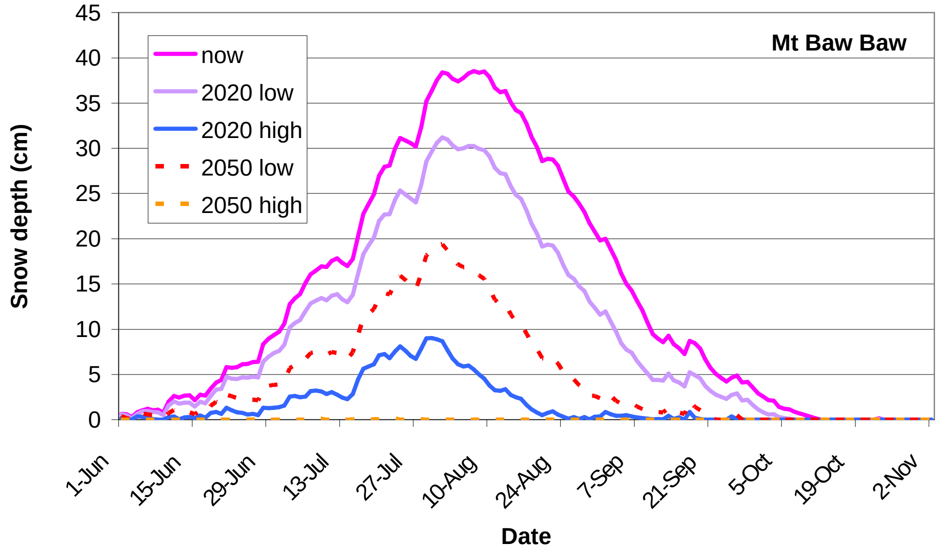

Figure 16: Simulated 20-year average snow-depth profiles at Mt Baw Baw (1,560 m) for present (1979-1998), 2020 and 2050. See Appendix 2 for limitations of these data.

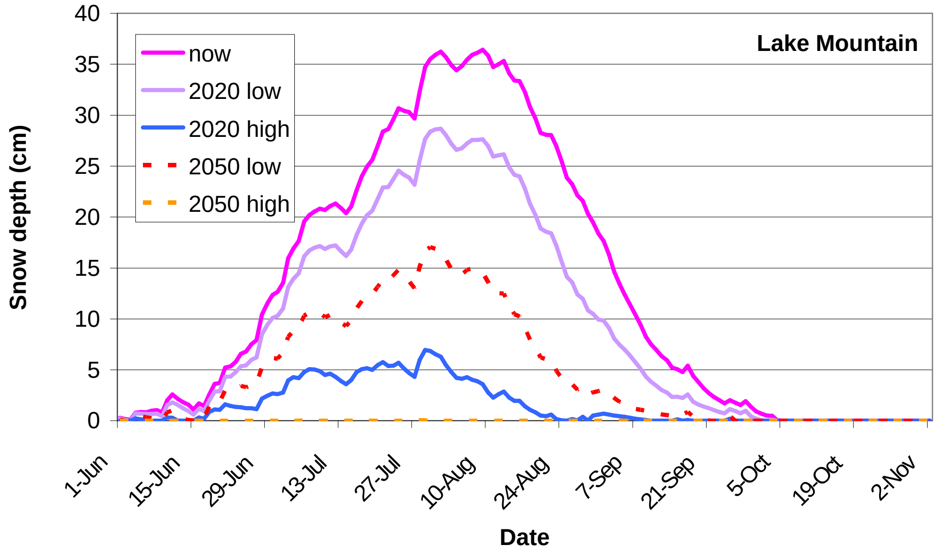

Figure 17: Simulated 20-year average snow-depth profiles at Lake Mountain (1,400 m) for present (1979-1998), 2020 and 2050. See Appendix 2 for limitations of these data.

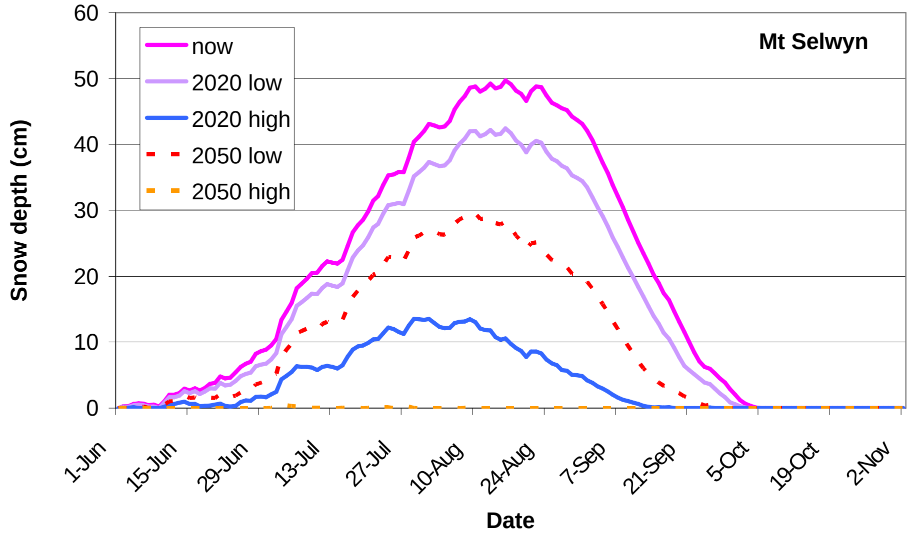

Figure 18: Simulated 20-year average snow-depth profiles at Mt Selwyn (1,604 m) for present (1979-1998), 2020 and 2050.

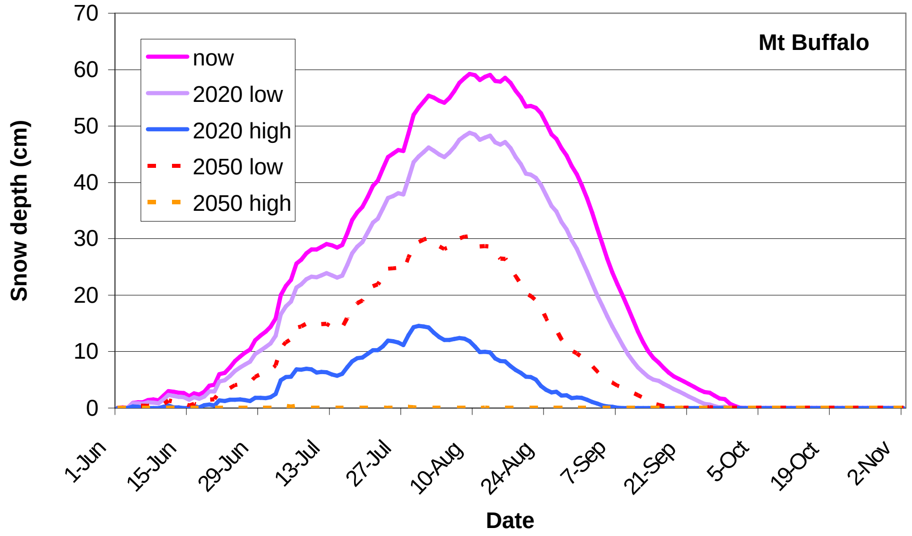

Figure 19: Simulated 20-year average snow-depth profiles at Mt Buffalo (1,516 m) for present (1979-1998), 2020 and 2050.

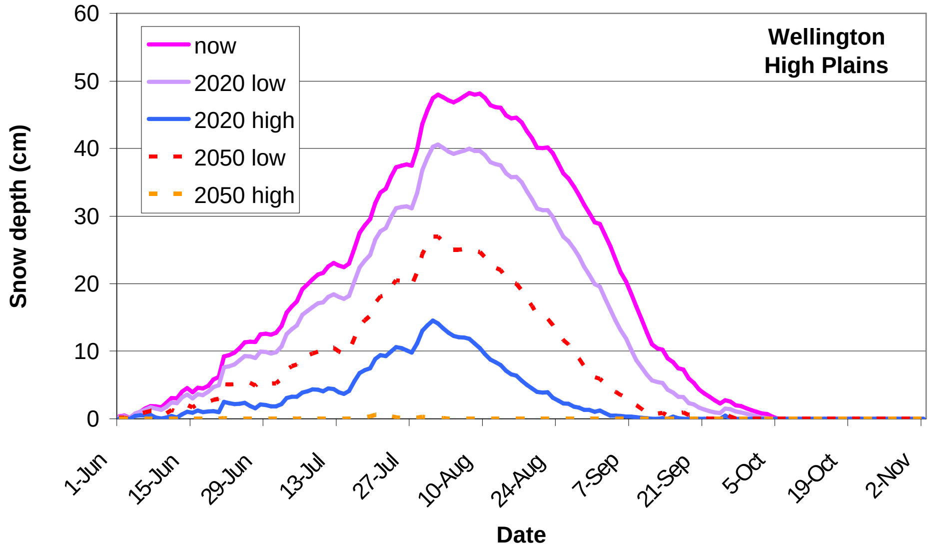

Figure 20: Simulated 20-year average snow-depth profiles at Wellington High Plains (1,560 m) for present (1979-1998), 2020 and 2050. See Appendix 2 for limitations of these data.

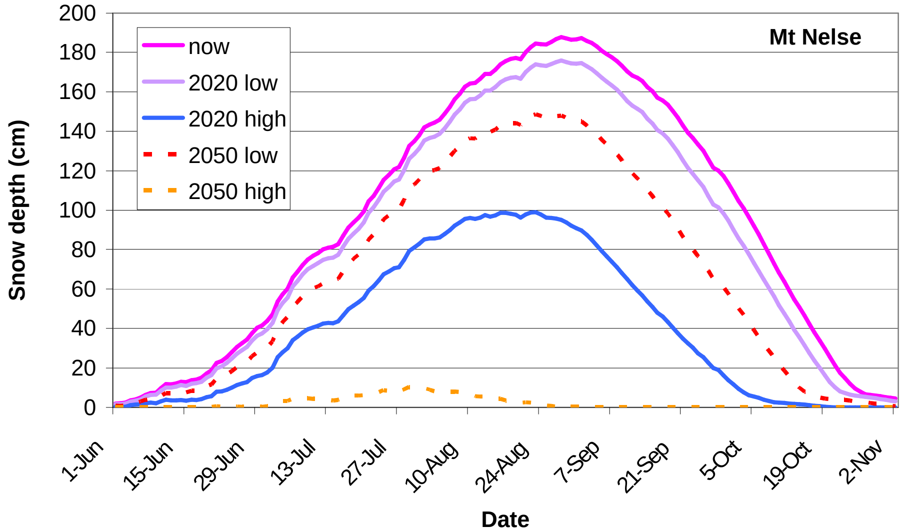

Figure 21: Simulated 20-year average snow-depth profiles at Mt Nelse (1,829 m) for present (1979-1998), 2020 and 2050.

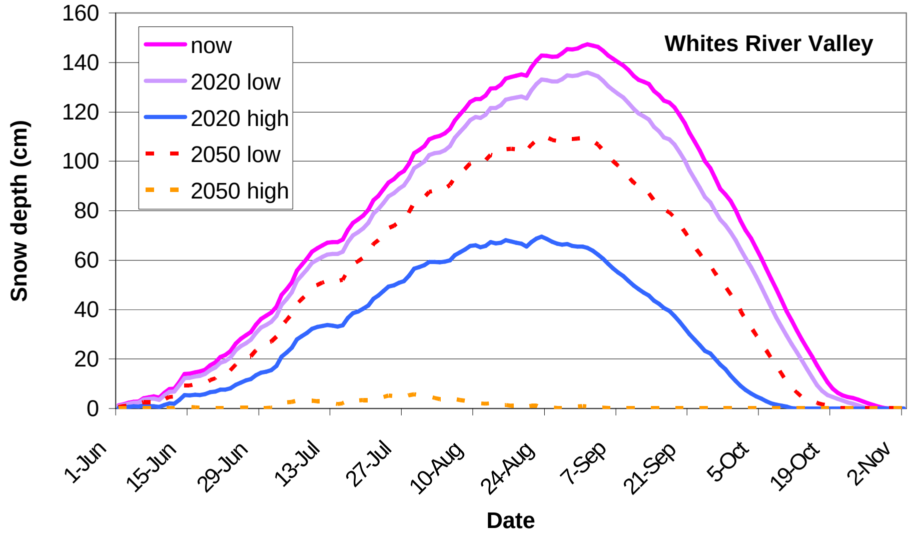

Figure 22: Simulated 20-year average snow-depth profiles at Whites River Valley (1,746 m) for present (1979-1998), 2020 and 2050.

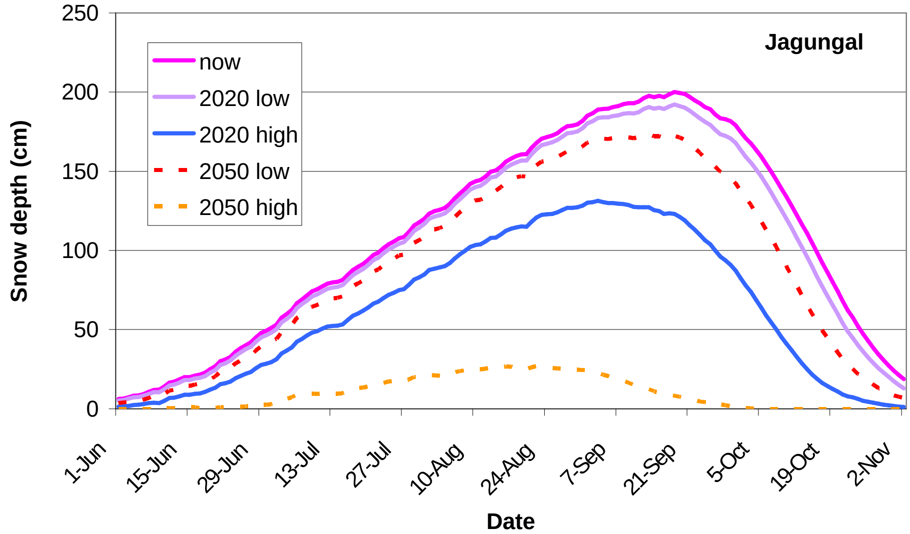

Figure 23: Simulated 20-year average snow-depth profiles at Mt Jagungal (2,061 m) for present (1979-1998), 2020 and 2050.

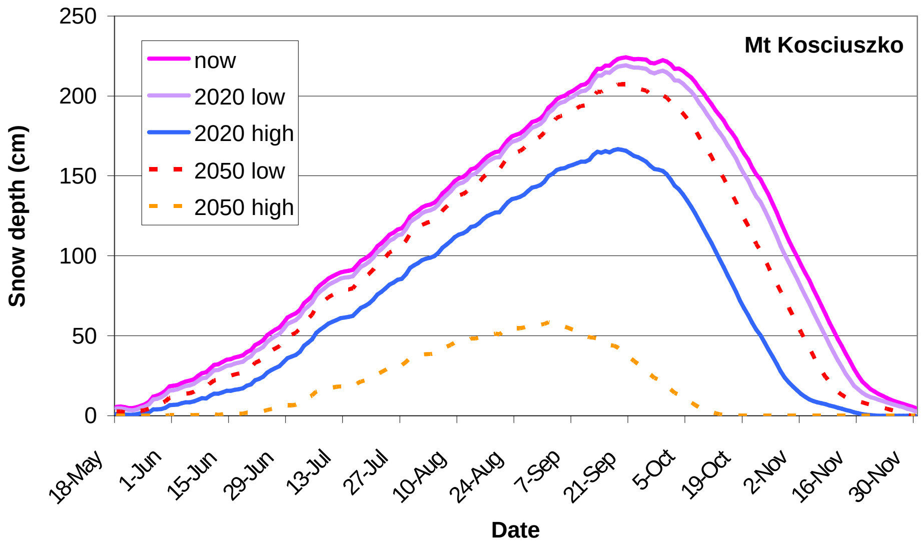

Figure 24: Simulated 20-year average snow-depth profiles at Mt Kosciuszko (2,228 m) for present (1979-1998), 2020 and 2050.

Table 6: Simulated average duration (days) of at least 1 cm of snow-cover at selected resorts (some with results for low, mid and high elevations) and sites of biological significance.

Site (elevation)	Present	2020	2050
Lake Mountain (1,400 m)	74	30-66	1-48
Mt Baw Baw (1,560 m)	80	32-71	1-53
Mt Buller low (1,383 m)	33	7-25	0-15
Mt Buller mid (1,560 m)	76	36-67	1-56
Mt Buller high (1,740 m)	108	70-102	7-89
Mt Buffalo low (1,477 m)	70	29-63	0-50
Mt Buffalo mid (1,516 m)	80	39-73	1-59
Mt Buffalo high (1,723 m)	113	78-108	10-96
Mt Wellington high plains (1,560 m)	82	38-75	2-59
Mt Nelse (1,829 m)	133	101-128	27-117
Falls Creek low (1,504 m)	77	41-71	2-59
Falls Creek mid (1,643 m)	105	68-99	8-87
Falls Creek high (1,797 m)	125	92-120	18-108
Mt Hotham low (1,400 m)	51	15-44	0-29
Mt Hotham mid (1,650 m)	98	59-92	4-77
Mt Hotham high (1,882 m)	129	97-124	21-114
Mt Perisher low (1,605 m)	90	53-87	4-69
Mt Perisher mid (1,835 m)	131	100-125	30-115
Mt Perisher high (2,021 m)	151	122-146	56-136
Mt Thredbo low (1,350 m)	32	8-26	0-17
Mt Thredbo mid (1,715 m)	113	80-108	13-97
Mt Thredbo high (2,023 m)	153	122-148	56-138
Mt Selwyn (1,604 m)	81	43-74	3-60
Whites River valley (1,746 m)	118	88-113	18-103
Mt Jagungal (2,061 m)	156	128-151	65-141
Mt Kosciuszko (2,228 m)	183	153-178	96-169

More detailed analysis of future snow conditions at selected sites

Elevation of the snowline

The daily elevation of the snowline was estimated for Mt Hotham by identifying the lowest snow-covered grid-point within 25 km. Results were averaged over the 20-year period 1979 to 1998 and plotted as a snowline profile throughout the year (Figure 25). For example, the snowline is predicted to rise from the present average of 1,412 metres on 1 September, to between 1,440 and 1,600 metres by 2020. At Mt Selwyn, the snowline on 1 September rises from 1,415 metres at present to between 1,500 and 1,660 metres by 2020. At Mt Kosciuszko, the snowline on 1 September rises from 1,460 metres at present to between 1,490 and 1,625 metres by 2020. As expected, there was little variation between sites in the behaviour of the snowline with warming.

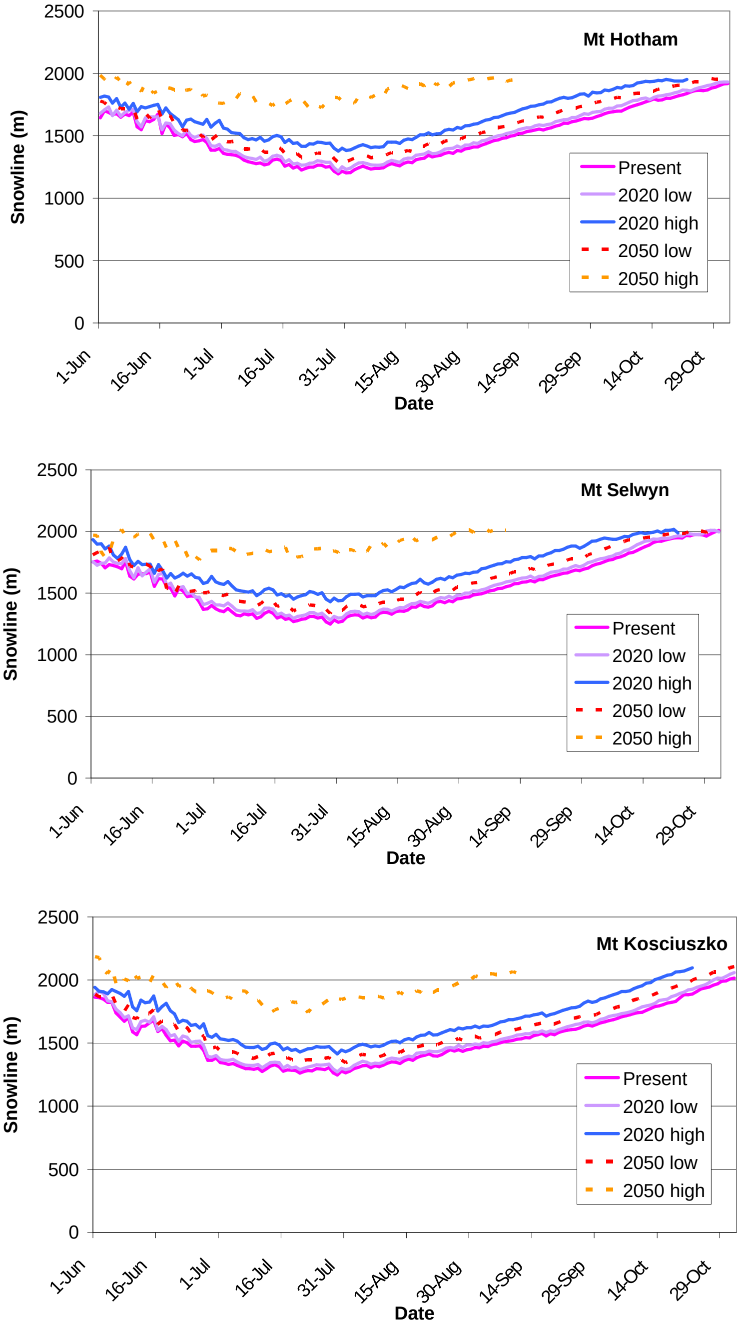

Figure 25: Simulated average snow-line elevation for Mt Hotham, Mt Selwyn and Mt Kosciuszko for present (1979-1998), 2020 and 2050. High impact scenarios are truncated when no snow is simulated.

Probability of exceeding 30 cm natural snow depth

The probability of exceeding a natural snow depth of 30 cm each day was calculated for Mt Hotham using data for 1979 to 1998 (Figure 26). For example, on 1 September, 18 of the 20 years had at least 30 cm of snow, so the present probability is 90%. By 2020, this probability is predicted to decline to between 60 and 85%. On 1 July, the probability drops from the present value of 65% to 15-60% by 2020.

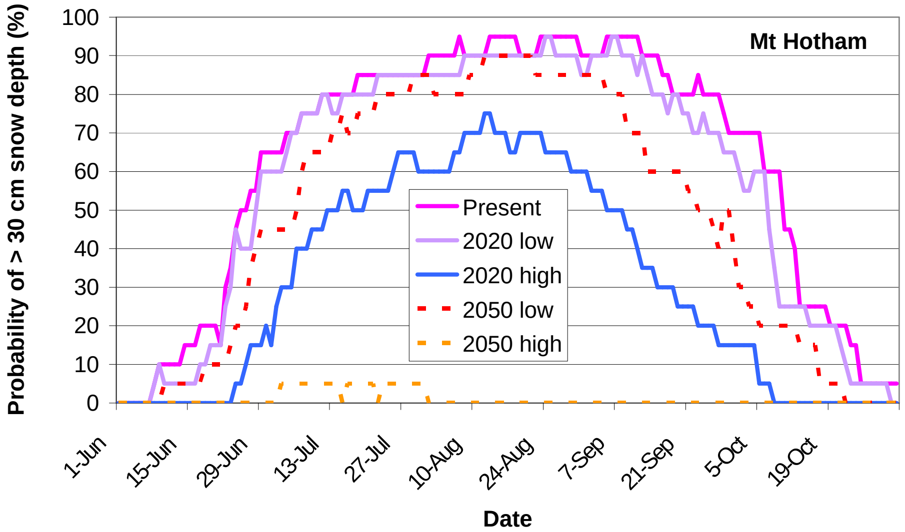

Figure 26: Simulated profiles of the probability of exceeding 30 cm natural snow depth at Mt Hotham (1,882 m) for present (1979-1998), 2020 and 2050.

Ratio of snow to rain

A decrease in the ratio of snow to rain in each precipitation event is expected as the climate warms, i.e. precipitation will tend to fall as rain rather than snow. The simulated ratio of snow to rain was calculated for Mt Hotham for the present (1979-1998), 2020 and 2050 (Figure 27). Changes by 2020 are small for the low impact scenario but significant for the high impact scenario. For example, on 1 September, the ratio declines from the present value of 4.2 to between 4.0 and 2.9 by 2020. This represents a decrease of 5-31%. On 1 July and 1 August, the present ratios are 5.2 and 5.7, respectively, and the decreases by 2020 are 0-16% and 1-23%, respectively.

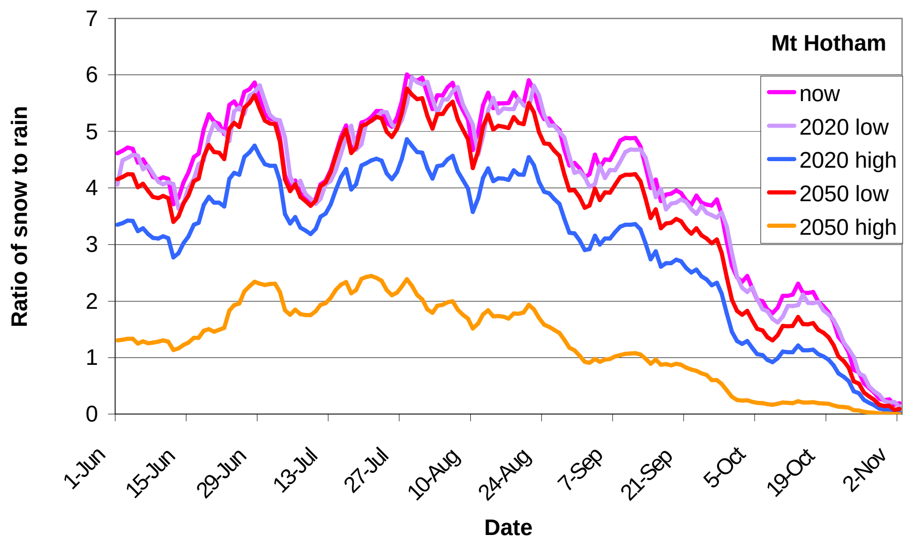

Figure 27: Simulated profiles of the ratio of snow to rain at Mt Hotham (1,882 m) for present (1979-1998), 2020 and 2050. An 11-day running mean has been used to smooth the data.

Daily rate of snow ablation

Greenhouse warming is likely to enhance the rate of ablation in future. The simulated daily rate of ablation was calculated at Mt Hotham (Figure 28). The low impact scenario for 2020 shows little change from present, but the high impact scenario for 2020 shows substantial increases during September, e.g. a 58% increase on 1 September. Results for a lower site (Mt Selwyn) and a higher site (Mt Kosciuszko) are also shown in Figure 28.

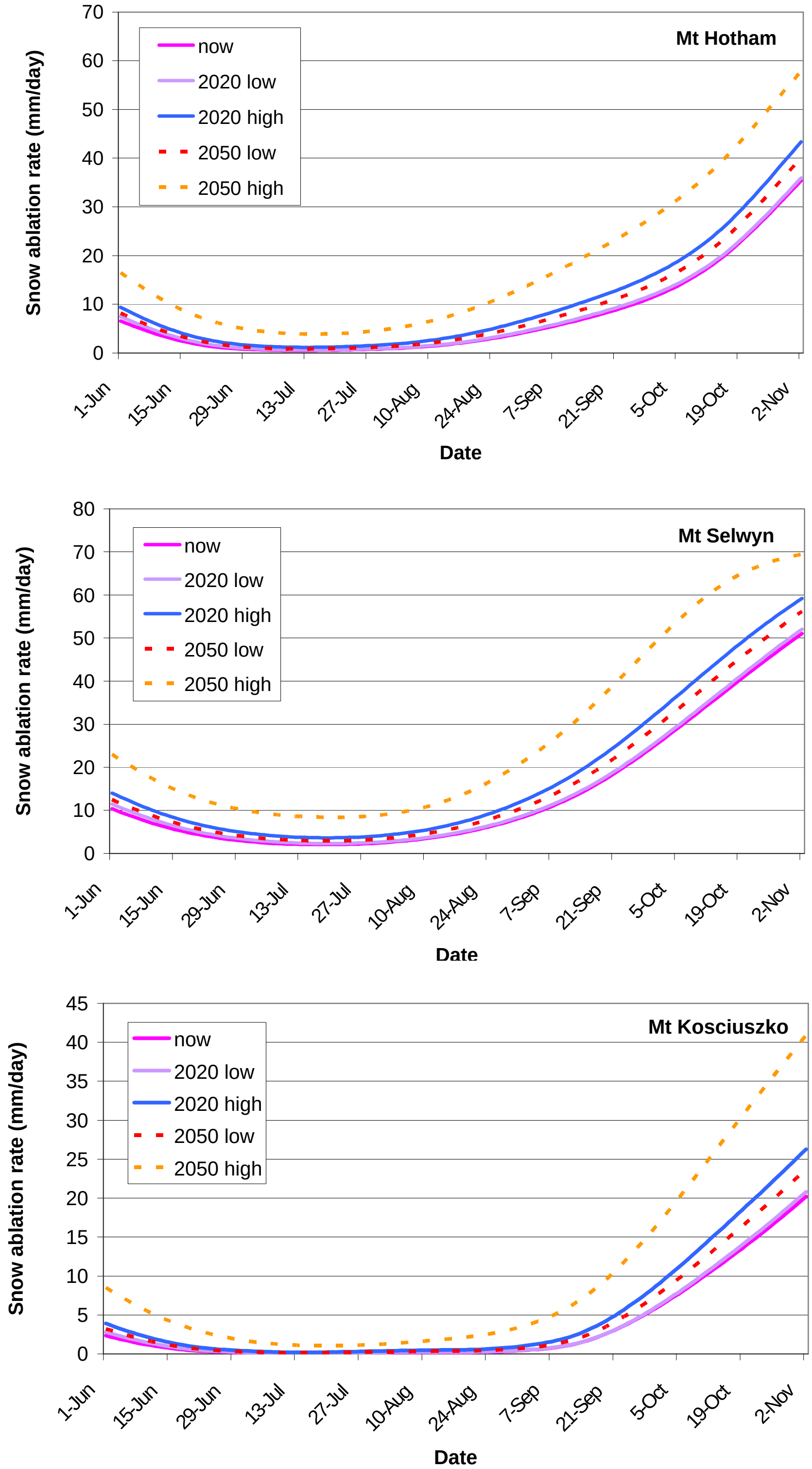

Figure 28: Simulated profiles of the daily snow ablation rate at Mt Hotham, Mt Selwyn and Mt Kosciuszko for present (1979-1998), 2020 and 2050. Units are water-equivalent mm per day.

Projected changes in snow-making requirements

A recent report on the Swiss ski industry (Elsasser and Bürki, 2002) notes that 85% of Switzerland's current ski resorts can be designated as having reliable natural snow, and this may decline to 44% over the coming decades if the elevation of reliable snow rose 600 metres due to greenhouse warming. The report concludes that climate change should be viewed as a catalyst for reinforcing and accelerating the pace of structural changes in alpine tourism. Various adaptation strategies are outlined (Figure 29) – adopting a fatalistic attitude toward climate change is unlikely since consumers and suppliers will undoubtedly alter their behaviour. Greenhouse warming over the coming decades will require adaptation by the ski industry through various operational and technical advances, many of which have been ongoing in the past decade, such as snow-making.

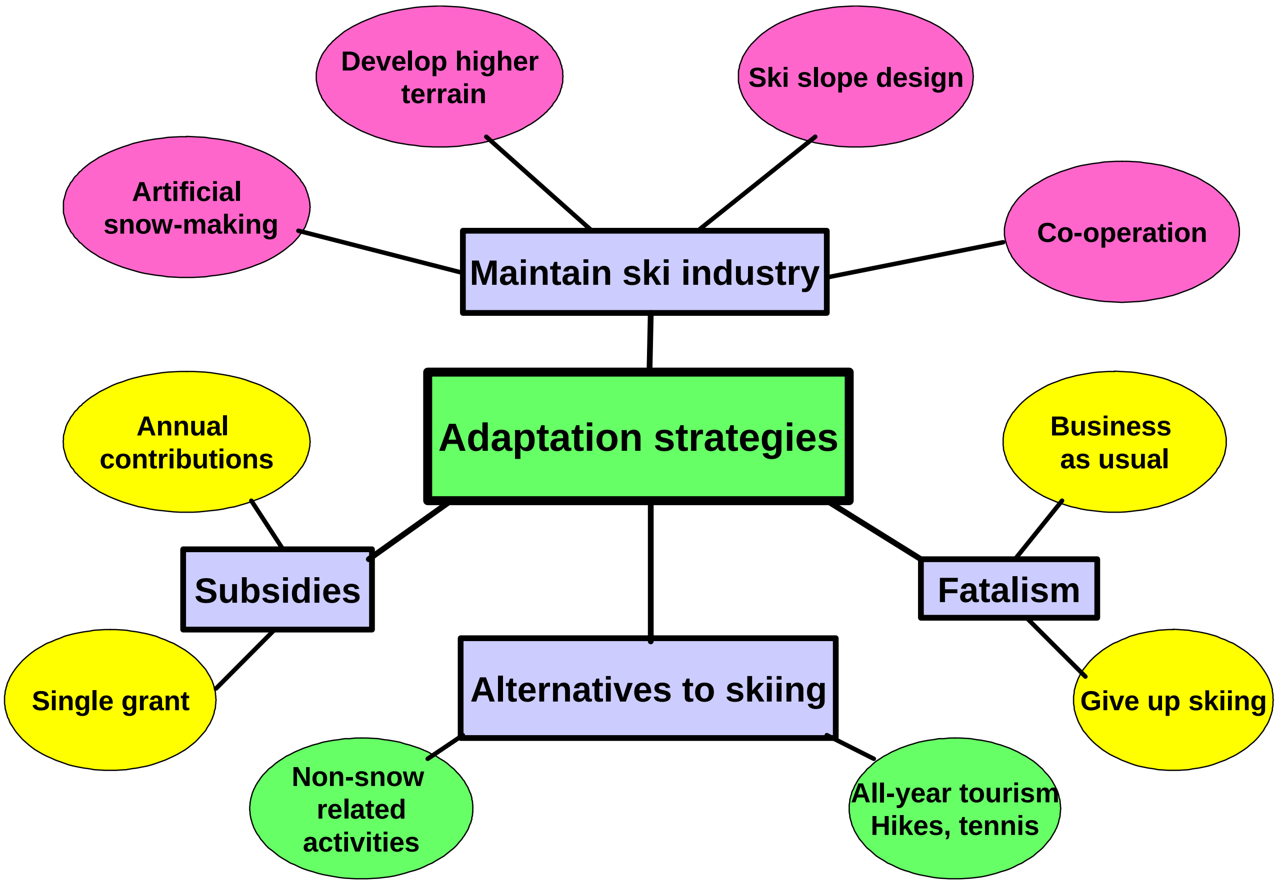

Figure 29: Possible adaptation strategies. Adapted from Elsasser and Bürki (2002).

Snow-making is used in Australia to supplement natural snow cover on heavily used or low-elevation ski runs and lift access areas (NPWS, 2001). Snow is usually guaranteed for the opening of the season in early June due to the availability of man-made snow. Snow-guns may be triggered automatically, by selected wet-bulb temperatures, or operated manually, with location, flow-rate and duration optimized to suit prevailing conditions. Snow fences and grooming are also important for creating and placing snow in the right location with some resorts selectively using nucleating agents to enhance snow-making efficiency (NPWS, 2001).

Scott et al. (2003) investigated the vulnerability of the southern Ontario (Canada) ski industry to climate change, including adaptation through snow-making. They used a 17-year record of daily snow conditions and operations from a major ski area to calibrate a ski season model including snow-making and operational decision rules based on interviews with ski area managers. The average ski season duration was projected to decline 0-16% by 2020, requiring a compensating increase in snow-making by 36-144%. They concluded that the southern Ontario ski areas could remain operational in a warmer climate within existing business planning and investment time horizons (into the 2020s). In our assessment for Australia, we have used a similar methodology to Scott el al. (2003).

Future demand for snow making will be influenced by:

1. Fewer hours with temperatures cold enough for making snow;
2. Less natural snow cover;
3. Faster ablation of snow;
4. Improvements in snow-making technology and operations;
5. The effect of cold air drainage on snow-making capacity at lower elevations;
6. The effect of topography and aspect on natural snow deposition; and
7. Possible water supply limitations and increased demand for water and power.

In our study, results are presented for the effects of factors 1, 2 and 3. The effect of factor 1 is presented first, followed by results for the combination of factors 1, 2 and 3. The exclusion of factors 4-7 are limitations of this study, outlined in more detail in the Conclusions.

Impact of greenhouse warming on potential snow-making hours and volume

Sub-zero wet-bulb temperatures are necessary for snow-making. Unlike dry-bulb temperature, wet-bulb temperature is influenced by humidity. Snow-making managers at most resorts were able to supply data showing the number of hours with wet-bulb temperatures in the range –2 to –12^{o}C, in 0.1^{o}C intervals, for May to September in various years between 1997 and 2002. Temperatures are lower at higher elevations, as shown by the annual number of hours below -5^{o}C in Figure 30, and this has a significant effect on the apparent snow-making capacity of each resort. Hence it is important to note the elevations at which the wet-bulb temperatures were measured (Table 7). Data for Mt Perisher and Mt Buller relate to a much higher elevation (1720 metres) than data for other resorts (e.g. 1340 metres at Mt Thredbo and Lake Mountain).

Wet-bulb warming scenarios for 2020 were derived from the output of ten climate models (Hennessy and Whetton, 2001) and applied to the observed hourly wet-temperature data at each resort. The warming was 0.2-0.9^{o}C at Mt Hotham and Falls Creek, and 0.1-0.7^{o}C at the other resorts. These changes are less than those for dry-bulb temperature (Table 4) due to regional changes in humidity associated with greenhouse warming. The average number of hours suitable for snow-making declines by 2-7% for the low impact scenario and by 17-54% for the high impact scenario (Figure 31).

Table 7: Locations of sites at which wet-bulb temperatures were measured during May to September in specified years at each resort. No data were available for Mt Hotham.

Resort	Years	Site(s)	Elevation (m)
Mt Perisher	1997-2001	Bottom of Perisher Express Quad Chair	1720
Mt Thredbo	1997-2001	Valley Terminal weather station	1340
Mt Selwyn	1997-2001	New Chum Beginner Bowl	1550
Falls Creek	1997-1999	Average of 5 sites	1642
Mt Buller	1997 & 2000	Average of 3 sites	1720
Mt Baw Baw	1998-2002	Bottom of Maltese Cross T Bar	1460
Lake Mountain	1997-2002	Gerratys	1340

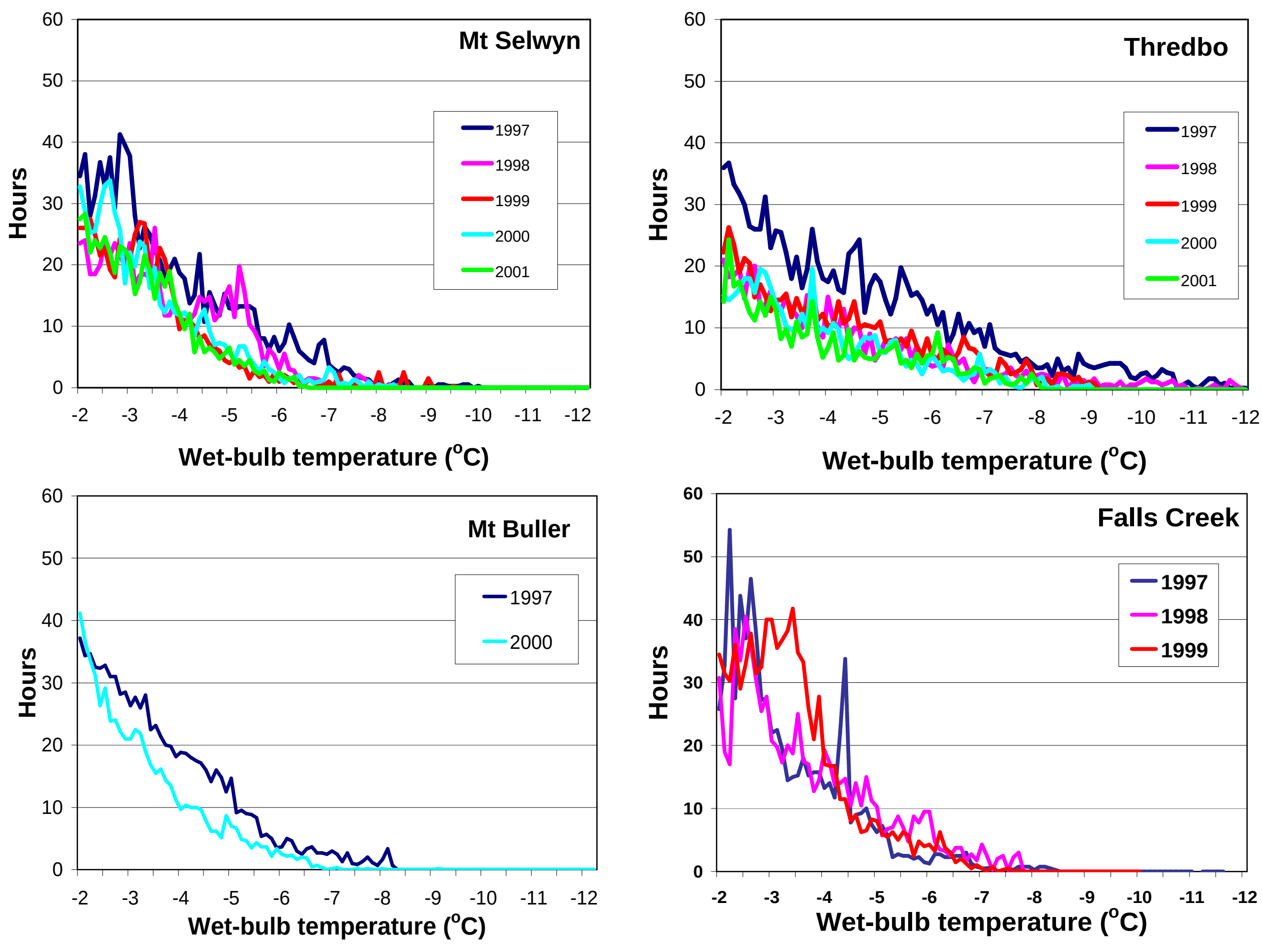

Figure 30: Total number of hours in wet-bulb temperature intervals of 0.1°C from May to September in various years at Mt Selwyn, Mt Thredbo, Mt Buller and Falls Creek.

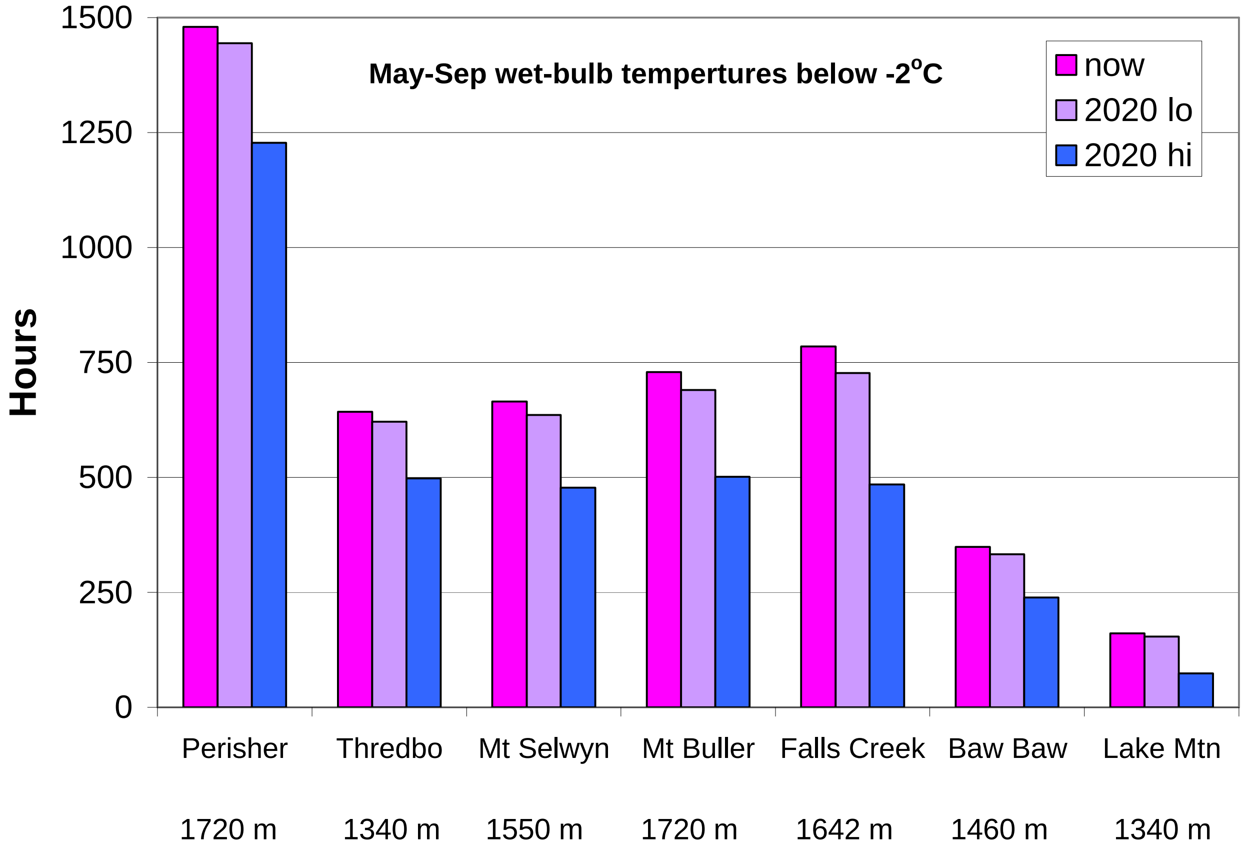

Figure 31: Average number of hours during May to September when wet-bulb temperatures were below -2°C for present (available years) and 2020. No wet-bulb temperatures were available for Mt Hotham.

To assess the impact of fewer snow-making hours on the volume of snow that could be made, we need to make some simplifying assumptions about snow-guns and how they are used. Resort operators have access to a range of snow-guns for making snow, each of which has different production characteristics. There are two basic types: air-water guns and fan guns. Each technology has strengths and weaknesses related to snow output, capital costs and operating costs. Most resorts have a mix of snow-making equipment operating at different pressures and water temperatures, sometimes automatically activated at selected temperatures and sometimes manually operated. In this study we assume automatic activation at temperatures below -2°C and unlimited water supply. Snow-gun specifications include the amount of water used (litres per second) for wet-bulb temperatures ranging from -2 to -12°C (Figure 32). At lower temperatures, more snow can be made and more water is used in the process. To simplify calculations, we limited our analysis to the Brand A air-water gun and Brand B fan gun (brand-names withheld for commercial reasons). At each resort, the wet-bulb temperatures were combined with water-flow specifications for each snow-gun to estimate the amount of snow that could have been produced each year – we define this amount as the *Potential Volume*. An average snow density of 0.4 was used to convert water volumes to snow volumes.

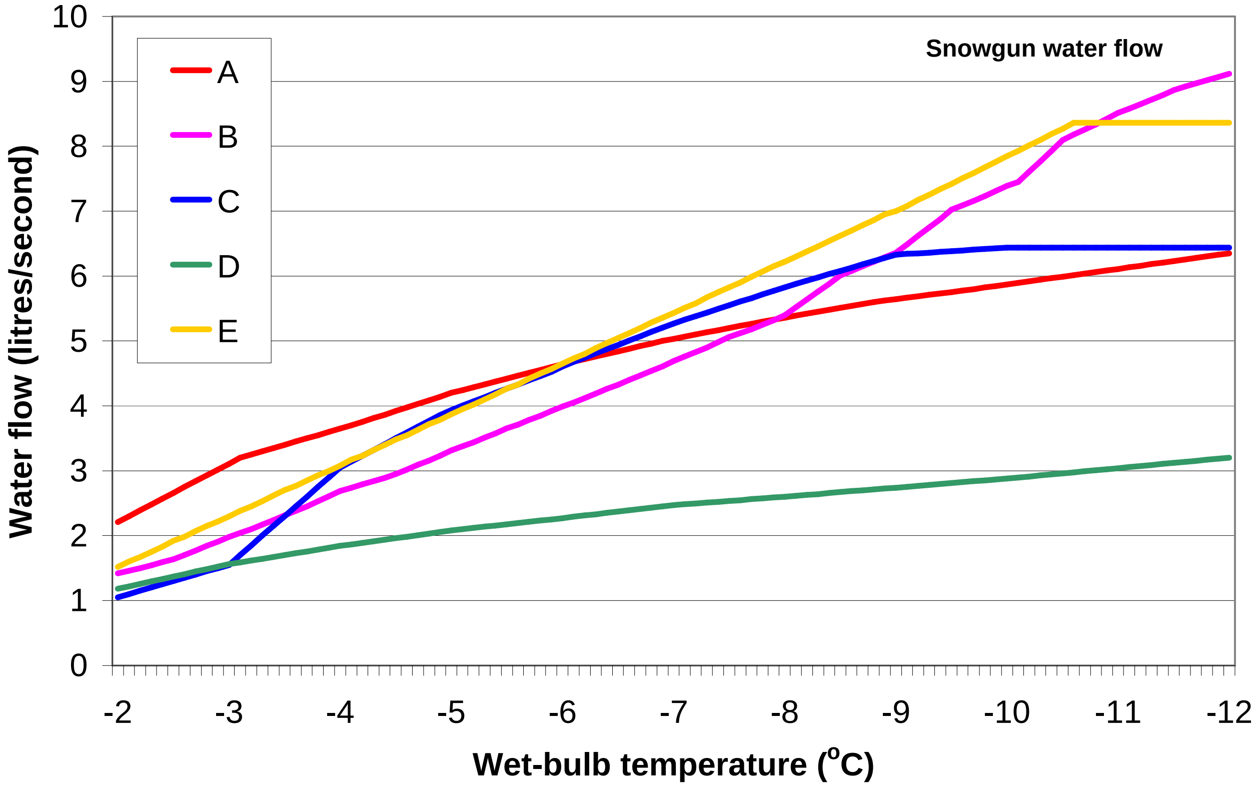

Figure 32: Water-flow specifications (litres/second) at various wet-bulb temperatures for a selection of snow-guns (Brands A, B, C, D, E) commonly used at Australian resorts.

Figure 33 shows the Potential Volume of snow that could have been made by each Brand A or Brand B snow-gun, based on the performance curves in Figure 32. Brand A snow-guns produced more snow at each resort than Brand B. Under the present climate, Mt Perisher showed the best snow-making capacity since it had the coldest wet-bulb temperature data for the highest elevation site. On average each year, Mt Thredbo, Mt Selwyn, Mt Buller and Falls Creek could produce about 20,000 cubic metres of snow using Brand A snow-guns, and about 15,000 cubic metres using Brand B. Mt Baw Baw could produce about half these amounts, and Lake Mountain could produce about one quarter. For both snow-guns, the potential snow volumes are reduced by 3-10% under the low impact scenario for 2020, and by 18-55% under the high impact scenario.

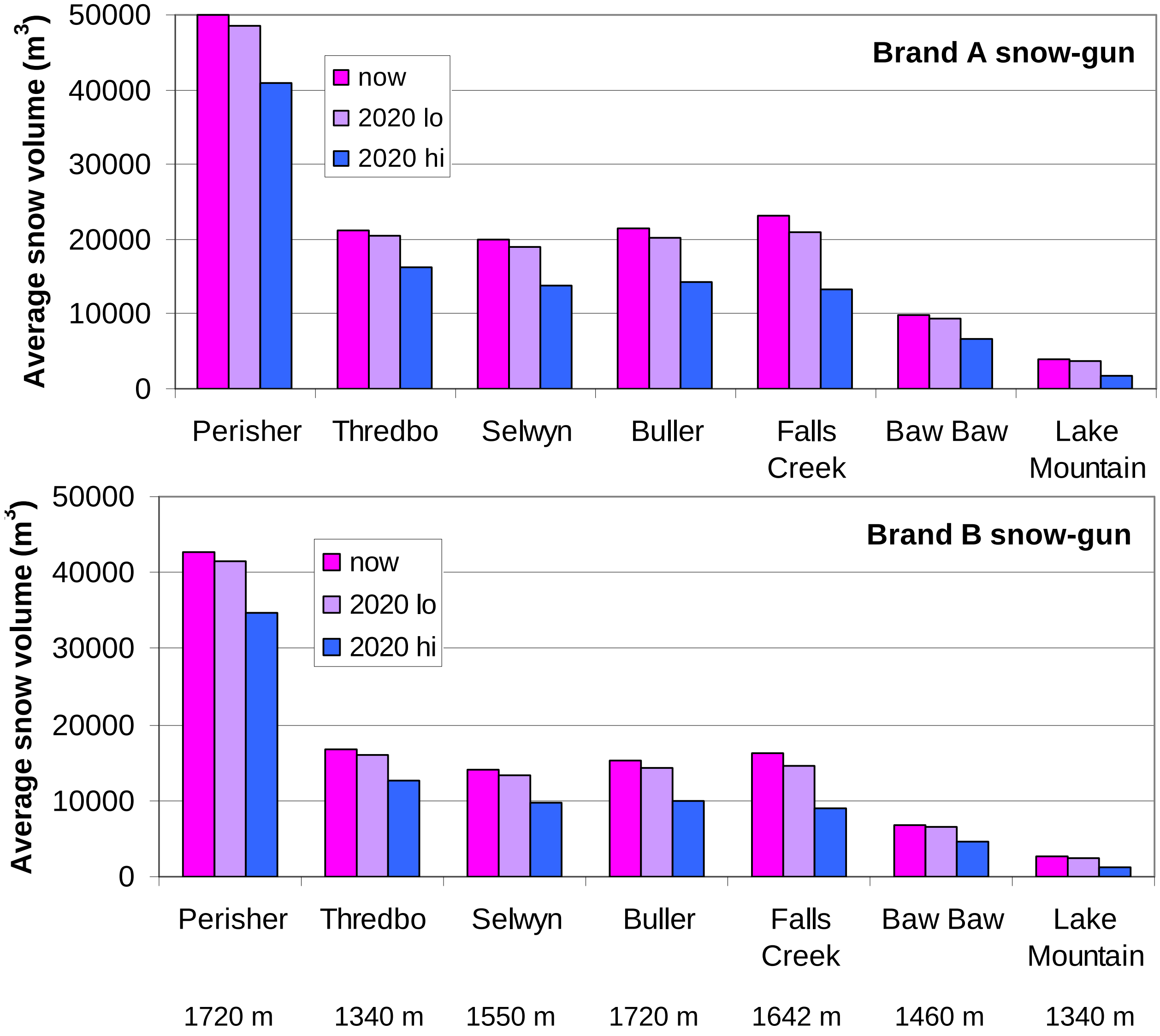

Figure 33: Average potential volume of snow (cubic metres) that could have been made during May to September by each Brand A or B snow-gun when wet-bulb temperatures were below –2°C for present (available years) and 2020. No wet-bulb temperature data were available for Mt Hotham.

Adapting to greenhouse warming through increased snow-making

The snow-making manager at each resort nominated a target depth profile for natural plus man-made snow, to be achieved 90% of the time. For example, at Mt Perisher, Mt Thredbo and Falls Creek, the profile was defined as 1 cm by 1 June, 30 cm by 30 June, 60 cm by 31 July, 100 cm by 31 August and 40 cm by 30 September (Table 8). Lower profiles were specified for Mt Buller, Mt Selwyn and Lake Mountain, reflecting their lower natural snow cover. The CSIRO daily snow model was modified to calculate the amount of man-made snow required to achieve these target depths, allowing for natural snowfall, ablation and the pre-existing natural snow-depth, as shown for Mt Hotham in 1997 in Figure 34.

Table 8: Target snow-depth (cm) profiles defined by snow-making managers at each ski resort. Results for Mt Hotham and Mt Baw Baw are not shown since monthly wet-bulb temperature data were unavailable. * Target depth at Mt Selwyn and Lake Mountain was 0 cm on 15 Sept.

Resort	1 June	30 June	31 July	31 August	30 Sept
Mt Perisher	1	30	60	100	40
Mt Thredbo	1	30	60	100	40
Mt Selwyn	1	20	30	45	0*
Falls Creek	1	30	60	100	40
Mt Buller	1	30	50	90	20
Lake Mountain	1	30	30	30	0*

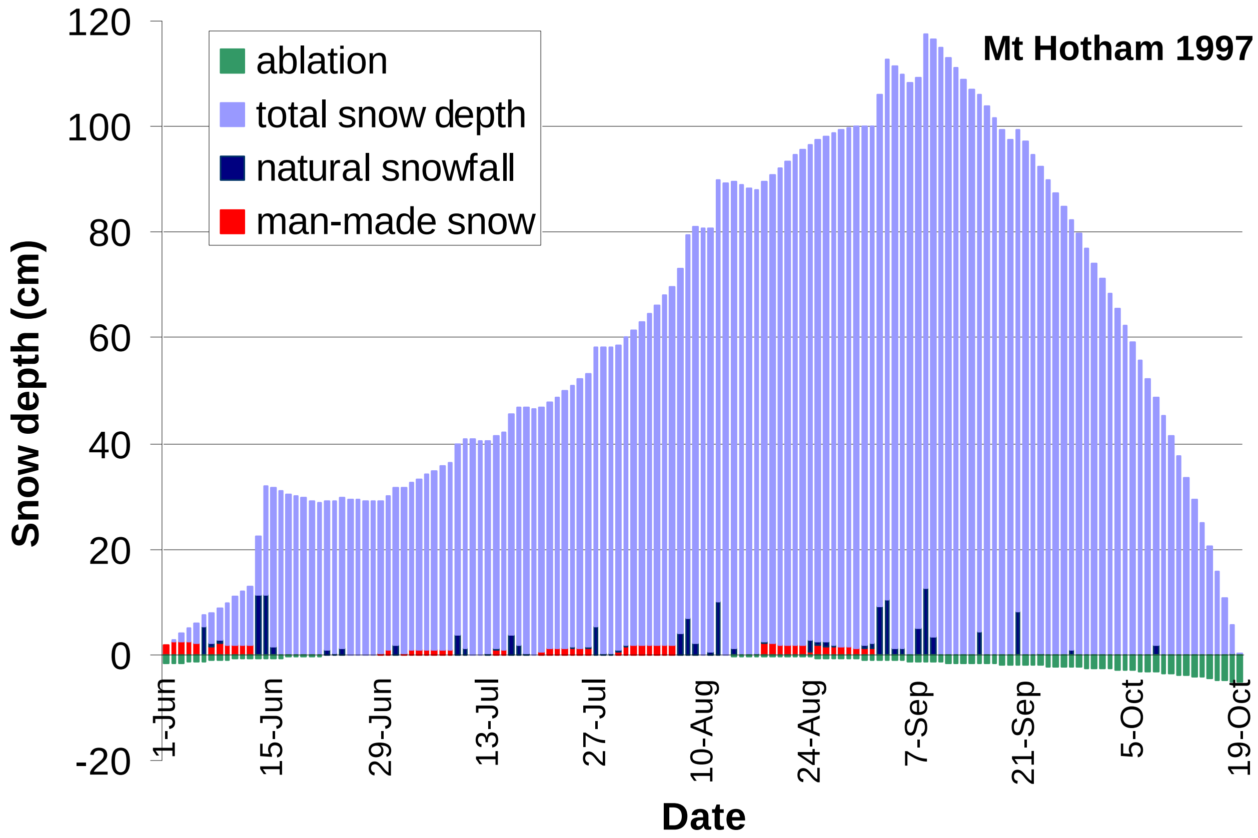

Figure 34: Simulated daily snowfall, ablation and man-made snow required to meet the target snow-depth profile from 1 June to 30 September 1997. The target depths are 30 cm on 30 June, 60 cm on 31 July, 100 cm on 31 August and 40 cm on 30 September.

The snow model simulated the daily snowfall, snow-melt and man-made snow required to meet the target snow depth profiles from 1950 to 1998 at each resort. According to the simulations, June and September were the months in which most man-made snow was needed. The accumulated monthly man-made snow depth for Mt Hotham is shown in Figure 35. An accumulated depth of 43.4 cm was required to ensure that 90% of Junes reached the target total depth (i.e. the 5th greatest depth in 49 years, which was the 1980 value in Figure 35).

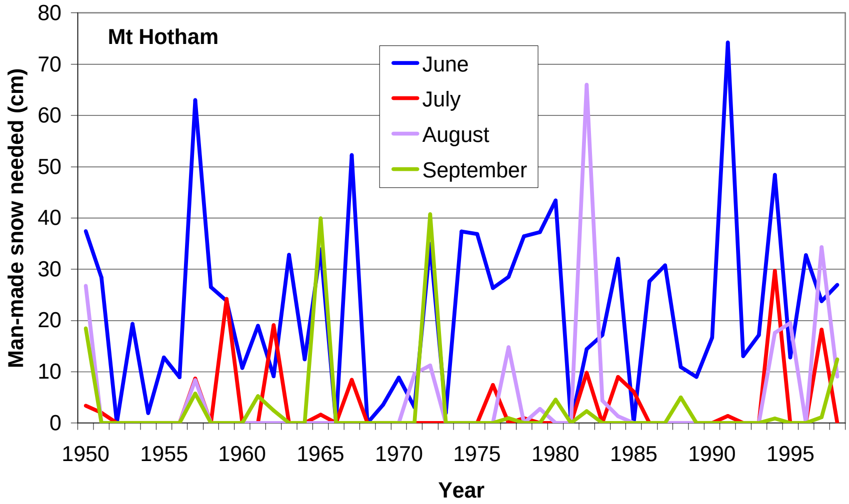

Figure 35: Monthly accumulated man-made snow depths required to meet the target snow-depth profile at Mt Hotham from 1950 to 1998. The target depths are 30 cm on 30 June, 60 cm on 31 July, 100 cm on 31 August and 40 cm on 30 September.

A typical ski run is about 500 metres long and 40 metres wide, with an area of 20,000 m^2. We calculated that 8,687 m^3 of snow would be required to cover a typical ski run at Mt Hotham in 90% of Junes. This was defined as the *Target Volume* for Mt Hotham. Different resorts had different Target Volumes, based on the combination of site-specific natural snowfall, snow-melt and target snow depths. Using information about the Potential Volume of snow that could be made (Figure 33), we can estimate the number of Brand A or Brand B snow-guns needed to achieve the Target Volumes, under present and 2020 conditions. The June and September versions of Figure 33 (not shown) were used since these were the months with greatest need for snow-making.

Sample Calculation

> At Falls Creek, each Brand A snow-gun could have produced 3451 m^3 in June 1997, 7562 m^3 in June 1998 and 5008 m^3 in June 1999. Therefore, the average Potential Volume was 5340 m^3 per gun. Under present conditions, the Target Volume at Falls Creek is 9614 m^3. Hence, the target depth on a typical ski run could be achieved in 90% of Junes with 1.8 Brand A guns per ski-run (i.e. 9614/5340). The low impact scenario for 2020 reduced the average volume per gun to 4880 m^3 and increased the target volume to 10,315 m^3, so the number of Brand A guns needed to achieve the target volume increased to 2.1 per ski run. Similarly, the high impact scenario for 2020 required 5.1 Brand A guns per ski run.

The results are significantly influenced by the elevations at which snow-making hours were computed, i.e. 1340 metres at Lake Mountain and Mt Thredbo, 1460 metres at Mt Baw Baw, 1550 metres at Mt Selwyn, 1642 metres at Falls Creek and 1720 metres at Mt Buller and Mt Perisher. Under present conditions, about one Brand A gun per ski run is needed at Mt Perisher, 1.8 at Falls Creek, and almost three at Mt Selwyn and Mt Buller (Figure 36). At Lake Mountain, 15 Brand A guns per ski-run would be needed (not shown). An increase of 11-24% in the number of these snow-guns would be required under the low impact scenario for 2020: 11% at Mt Selwyn, 12% at Mt Thredbo, 14% at Mt Perisher and Lake Mountain, 17% at Falls Creek and 24% at Mt Buller. Under the high impact scenario for 2020, a 73-200% increase in snow-guns is needed: 73% at Mt Perisher, 85% at Mt Thredbo, 94% at Mt Selwyn, 142% at Falls Creek, 181% at Mt Buller and 200% at Lake Mountain. Different results would be obtained if different target snow-depth profiles were specified in Table 8. Brand B snow-guns produce slightly less snow than Brand A. Under present conditions, about one Brand B gun per ski run is needed at Mt Perisher, 2.6 at Falls Creek and Mt Thredbo, 4.2 at Mt Selwyn and Mt Buller, and 21 at Lake Mountain. An increase of 11-27% in the number of these snow-guns would be required under the low impact scenario for 2020: 11% at Mt Selwyn, 12% at Mt Thredbo, 14% at Mt Perisher, 15% at Lake Mountain, 18% at Falls Creek and 27% at Mt Buller. Under the high impact scenario for 2020, a 71-188% increase in Brand B snow-guns is needed: 71% at Mt Perisher, 90% at Mt Thredbo, 97% at Mt Selwyn, 151% at Lake Mountain, 171% at Mt Buller and 188% at Falls Creek.

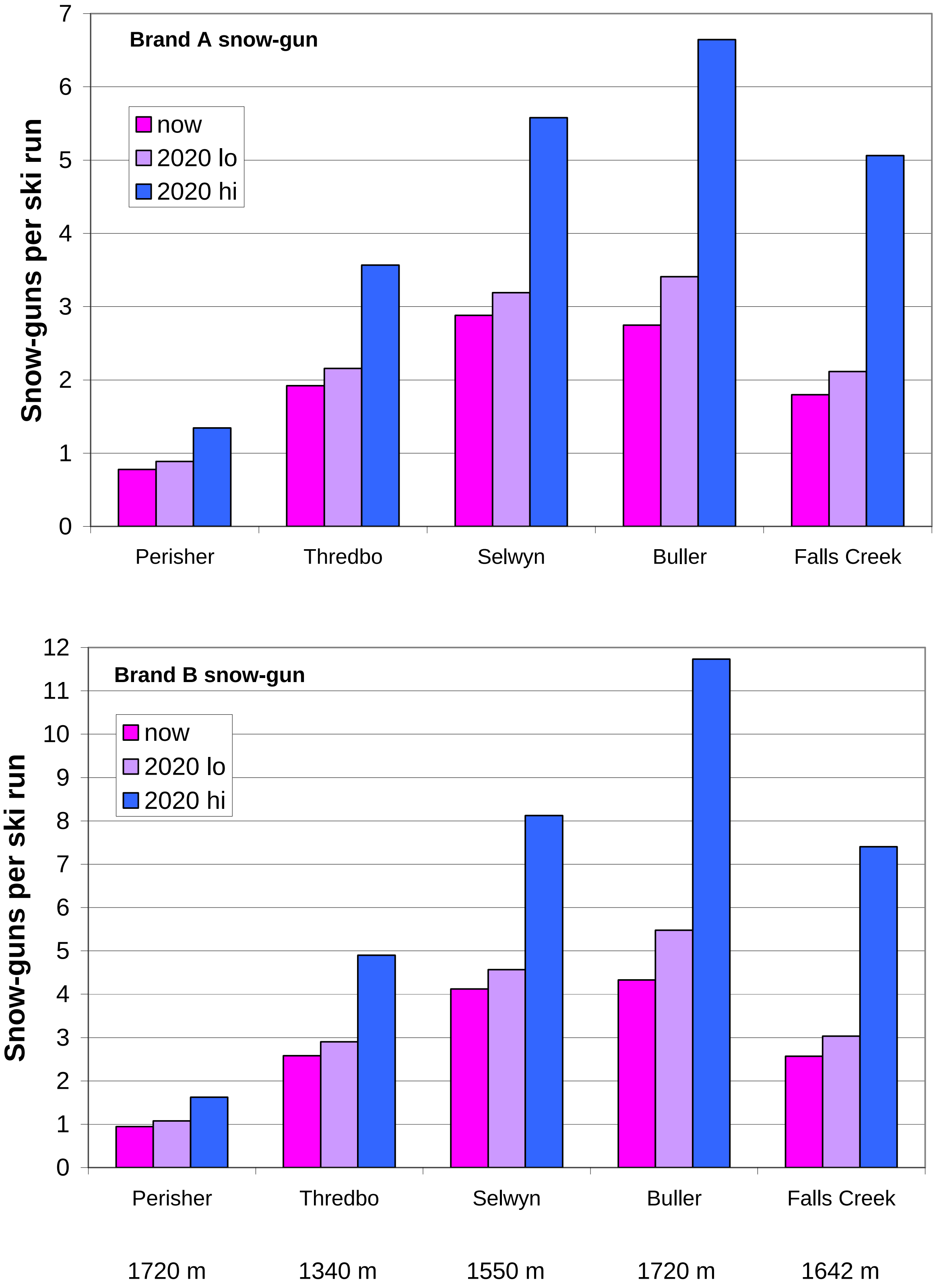

Figure 36: Number of Brand A or Brand B snow-guns needed to achieve resort-specific target snow-depth profiles (Table 8) in 90% of Junes on a typical ski run measuring 500m x 40 m, for present and 2020 conditions.

Conclusions

Warming trends at four alpine sites over the past 35 years appear to be greater than trends at lower elevations. There is evidence of small alpine precipitation changes over the past 50 years, with increases in the New South Wales Alps and decreases in the Victorian Alps. A weak decline in maximum snow depth is evident at three of the four alpine sites analysed since the 1950s. A decline in season snow depths for August and September is evident at three sites which may indicate the tendency for warmer temperatures to reduce both the snow-to-rainfall ratio and increase the rate of melting.

The low impact scenario for 2020 has a minor impact on snow conditions. Average season lengths are reduced by around five days. Reductions in peak depths are usually less than 10%, but can be larger at lower sites (e.g. Mt Baw Baw and Wellington High Plains). The high impact scenario for 2020 leads to reductions of 30-40 days in average season lengths. At higher sites such as Mt Hotham, this can represent reductions in season duration of about 25%, but at lower sites such as Mt Baw Baw the reduction can be more significant (up to 60%). Impacts on peak depth follow a similar pattern: moderate impacts at higher elevation sites, large impacts at lower elevation sites. There is also a tendency for the time of maximum snow depth to occur earlier in the season under warmer conditions. For example, the results for Mt Thredbo show this occurring about 20 days earlier under the high impact scenario.

The snowline is expected to rise with global warming. For example, at Mt Kosciuszko, the snowline elevation on 1 September is predicted to rise from the present average of 1,460 metres to between 1,490 and 1,625 metres by 2020. The probability of exceeding a natural snow depth of 30 cm each day also declines with greenhouse warming. For example, at Mt Hotham on 1 July, the probability drops from the present value of 65% to 15-60% by 2020.

Under the low impact scenario for 2050, season durations are decreased by 15-20 days at most sites. Such reductions are relatively minor at high sites but can represent a substantial impact at low sites. The reductions in peak depths range from around 10% at the highest sites to more than 80% at low sites such as Mt Baw Baw. The high impact scenario for 2050 leads to very large reductions in season duration and peak depth at all sites. Season durations are typically reduced by around 100 days, which leaves only the highest sites with durations of more than ten days. Maximum depths shrink to less than 10% of their present value and occur much earlier in the season

Adaptation to climate change will be necessary at all ski resorts. An obvious strategy is to make more snow using snow-guns. The Potential Volume was defined as the amount of snow that could be made using two typical snow-guns at each resort, based on information about the snow-gun performance and the frequency of wet-bulb temperatures suitable for snow-making. Brand A snow-guns produced more snow at each resort than Brand B. The results are significantly influenced by the elevations at which snow-making hours were computed, i.e. 1340 metres at Lake Mountain and Mt Thredbo, 1460 metres at Mt Baw Baw, 1550 metres at Mt Selwyn, 1642 metres at Falls Creek and 1720 metres at Mt Buller and Mt Perisher.

On average each year, Mt Perisher could produce about 50,000 cubic metres of snow per Brand A snow-gun. Mt Thredbo, Mt Selwyn, Mt Buller and Falls Creek could produce about 20,000 cubic metres of snow per Brand A snow-gun, and about 15,000 cubic metres per Brand B snow-gun. Mt Baw Baw could produce about half these amounts, and Lake Mountain could produce about one quarter. For both snow-guns, the average number of hours suitable for snow-making declines by 2-7% for the low impact scenario and by 17-54% for the high impact scenario. The potential snow volumes are reduced by 4-10% under the low impact scenario, and by 27-55% under the high impact scenario.

Based on target snow-depth profiles nominated by snow-making managers at each resort, we used the snow model to simulate the amount of man-made snow required, taking into account natural snowfall, snow-melt and the pre-existing natural snow depth. Using information about Potential Volume of snow that could be made, we estimated the number of snow-guns needed to achieve the target depth profiles over a typical ski-run 90% of the time, under present and 2020 conditions. About one Brand A gun per ski run is needed at Mt Perisher under present conditions, 1.8 at Falls Creek, almost three at Mt Selwyn and Mt Buller, and 15 at Lake Mountain. An increase of 11-24% in the number of Brand A snow-guns would be required for the low impact scenario, and 73-200% for the high impact scenario. Brand B snow-guns produce slightly less snow than Brand A. Under present conditions, about one Brand B gun per ski run is needed at Mt Perisher, 2.6 at Falls Creek and Mt Thredbo, 4.2 at Mt Selwyn and Mt Buller, and 21 at Lake Mountain. An increase of 11-27% in the number of these snow-guns would be required for the low impact scenario, and 71-188% for the high impact scenario. Therefore, with sufficient investment in snow-guns, the Australian ski industry will be able to manage the impact of projected climate change until at least 2020, bearing in mind the limitations outlined below.

This study has made some simplifying assumptions and excluded a number of physical and management effects that are not easily included in CSIRO's modeling framework. Apart from limiting results to the two snow-guns, operated automatically at all resorts, exclusions were:

- likely improvements in snow-making technology;
- improvements in snow-making operations, e.g. optimizing start-up temperatures, managing the number of pumps and pressure gradients to minimize water heating, improving efficiency of water cooling systems, plume placement, elevating guns on towers, additives to enhance conversion of water to snow, snow grooming and snow-farming, the effect of cold air drainage on snow-making capacity at lower elevations;
- effect of topographic aspect on natural snow deposition;
- reduced ablation rate for man-made snow relative to natural snow;
- possible water-supply limitations due to projected climate change;
- acceptable levels of environmental impact, e.g. likely increase in demand for water and energy due to increased snow-making.

Research needed to address gaps in knowledge

There is significant potential to widen the scope of the current study, and to address uncertainties and gaps in knowledge, through further research.

Accuracy of the modeling of natural snow cover could be improved by using daily temperature information, rather than the monthly temperature data currently used. Daily data would allow more accurate estimation of the proportion of precipitation falling as snow, and would be likely to improve snow simulation in southern areas of the Alps where the current methods based on monthly data are likely to be less reliable. More generally, year to year and within-year fluctuations in snow depth would be improved. It would also allow full integration of the modeling of natural and man-made snow (see below).

There is also a need to improve the accuracy of the observed climate data sets in the southern Victorian alpine region, to address problems described in Appendix 2.

Time and resource limitations required us to simulate natural snow cover and man-made snow production with separate datasets (with very different time periods) and models. Although it was then possible to compare the results to make some assessment of the industry's capacity to use snow-making to adapt to climate change, more accurate results would have been obtained from an integrated modeling system which simultaneously modeled both natural snow and man-made snow using a consistent daily dataset – this type of approach was used recently in the Canadian study by Scott et al. (2003). It would also be appropriate to make allowance for differing ablation-rates of man-made and natural snow in the modeling system. It would be beneficial to consider the water supply and energy implications of increased snow-making.

The geographical scope of the study could expanded to include alpine areas in Tasmania. Comparison with impacts in other skiing regions such as New Zealand, Canada, USA and Europe could also be considered. The impact on Australian alpine biodiversity should also be considered.

Acknowledgements

The climate model data were generously provided by climate modellers at CSIRO, the Canadian Climate Centre, Deutsches Klimarechenzentrum in Germany, the U.S. Geophysical Fluid Dynamics Laboratory, the U.S. National Center for Atmospheric Research, and the U.K. Hadley Centre for Climate Prediction and Research. Dr David Etheridge (CSIRO) provided useful comments on the manuscript.

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Appendix 1 Methodology

Collection and preparation of observed climate databases

In the study by Whetton (1998), the CSIRO snow model was driven with monthly temperature and precipitation data from 1966 to 1985 on a 1/40th degree grid (about 2.5 km). To enhance performance of the model, the ANU Centre for Resource and Environmental Studies (ANU CRES) developed improved databases for elevation, temperature and precipitation on the same grid, and extended the monthly climate datasets from 1951 to 2000.

The climate grids were created by fitting thin plate smoothing splines, dependent on longitude, latitude and elevation, to climate-station data recorded by the Australian Bureau of Meteorology as described in Hutchinson (1991), and then calculating the surfaces on a digital elevation model. The thin plate smoothing splines were calculated by Version 4.3 of the ANUSPLIN software package (Hutchinson 2001). Recent advances in this package include dependent variable transformations and the ability to process incomplete data sets. A square root transformation was applied to the precipitation data to remove the natural skewness in these data. This had the advantages of reducing interpolation error by equilibrating spatial variability between low precipitation areas and high precipitation areas and of delivering fitted surfaces that naturally gave rise to non-negative precipitation values.

Data for the monthly mean temperature and precipitation surfaces were first standardised to the period 1951 to 2000 by regressing short period records with nearby long period records. The regression with least estimated error was chosen for each short period record. Precipitation regressions were performed on the square root rainfalls to remove the effects of skewness, as was done for the spatial precipitation analyses. Appropriate bias corrections were made when the square root transformation was used. The monthly mean daily minimum temperature grids were supplied in ASCII Arc/Info grid format, with average estimated standard errors that ranged from 0.5^{o}C in winter to 0.7^{o}C in summer. The monthly mean daily maximum temperature grids had average estimated standard errors that ranged from 0.4^{o}C in winter to 0.6^{o}C in summer. The monthly precipitation grids had average estimated standard errors from 15 to 20% of the grid means. The errors were as low as 10% in wet winter months and greater than 20% in drier months.

For the analysis of alpine climate trends, several data sources were used.

- winter-average temperature data from the Bureau of Meteorology for 1950-2001 on a ¼ degree grid (about 25 km);
- winter-average precipitation data from the Bureau of Meteorology for 1950-2001 on a ¼ degree grid (about 25 km);
- monthly-average precipitation data from ANU CRES for 1951-2000 on a 1/40th degree grid (about 2.5 km);
- daily temperature data for eight sites in south-eastern Australia, including four sites over 1,300 metres from around 1960 to present;
- snow depth data from Southern Hydro for Rocky Valley Dam from 1935 to 2002;
- snow depth data from Snowy Mountains Hydroelectric Authority http://www.snowyhydro.com.au/data/pdf/snowdepths.pdf for Spencers Creek (1954-2002), Deep Creek (1957-2002) and Three-Mile Dam (1955-2002).

Modifications to CSIRO’s snow model

The CSIRO snow model was developed by Whetton et al. (1996) from the model of Galloway (1988). The model is used to calculate snow duration and water-equivalent depth from monthly-average temperature and precipitation, and daily standard deviation of temperature. Empirically-derived relationships incorporating these parameters are used to calculate accumulation (snowfall) and ablation (melting and evaporation of snow) for each month. Accumulation depends on monthly precipitation and the proportion of precipitation falling as snow (which is temperature-dependent). Ablation is calculated from the number of degree-days above $0^{o}C$. The snow season begins when accumulation exceeds ablation, and the snow depth grows until ablation exceeds accumulation. The snow depth then falls until the excess of ablation over accumulation has been sufficient to melt all snow, at which point the season ends (Figure 1-A1).

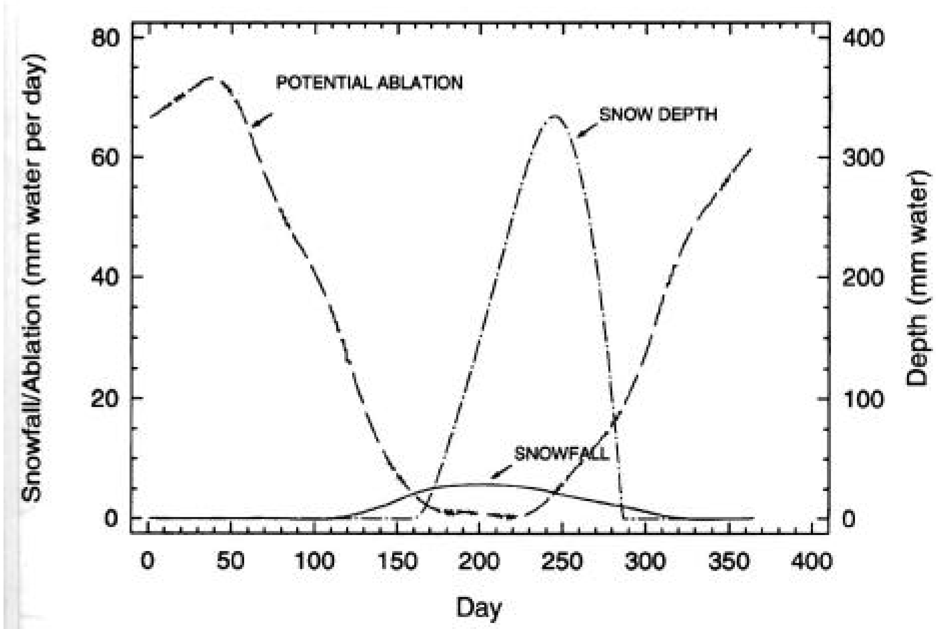

Figure 1-A1: Example of snow cover duration calculation for Mt Buller using the CSIRO snow model. The day number starts from 1 January. From Haylock et al. (1994).

Whetton et al. (1992) ran the snow model with average temperature and precipitation data on a 7 km grid to estimate average snow cover for present and future conditions. The model was subsequently improved by Haylock et al. (1994) who included interannual variability by using monthly-mean temperature and precipitation data on a finer resolution (2.5 km) grid from 1966-1985. Comparison of observed and simulated interannual changes in snow-cover duration allowed a more thorough validation and improvement of model performance. One of the limitations of the model was the underestimation of snow depths and durations at lower sites like Lake Mountain. It was recommended by Haylock et al. (1994) that “shorter simulated durations (less than around 30 days) should simply be viewed as ‘marginal’ and not interpreted literally”.

A key aim of the current project was to improve the performance of CSIRO's snow model at low-elevation sites by including daily sequences of precipitation and by using more accurate monthly input climate data generated at the ANU. A feature of the new model has been to change snow depth units from water-equivalent to snow-equivalent, thereby giving more relevant results for resort operators and natural resource managers. As a result of changes to the model, the new version gives a more realistic prediction of the marginal depths in low snow years.

Standard outputs of the snow model are now:

- snow depth;
- duration of snow cover;
- rate of ablation;
- snow-to-rainfall ratio;
- regional maps and site-specific snow-depth profiles;
- probability of snow depth at a given date;
- elevation of the snow-line.

A basic test of model performance is how well it reproduces the average snow-depth profile. Examples are shown in Figure 2-A1. The model performs well at all New South Wales and north-eastern Victorian sites where observed snow depth data were available for validation.

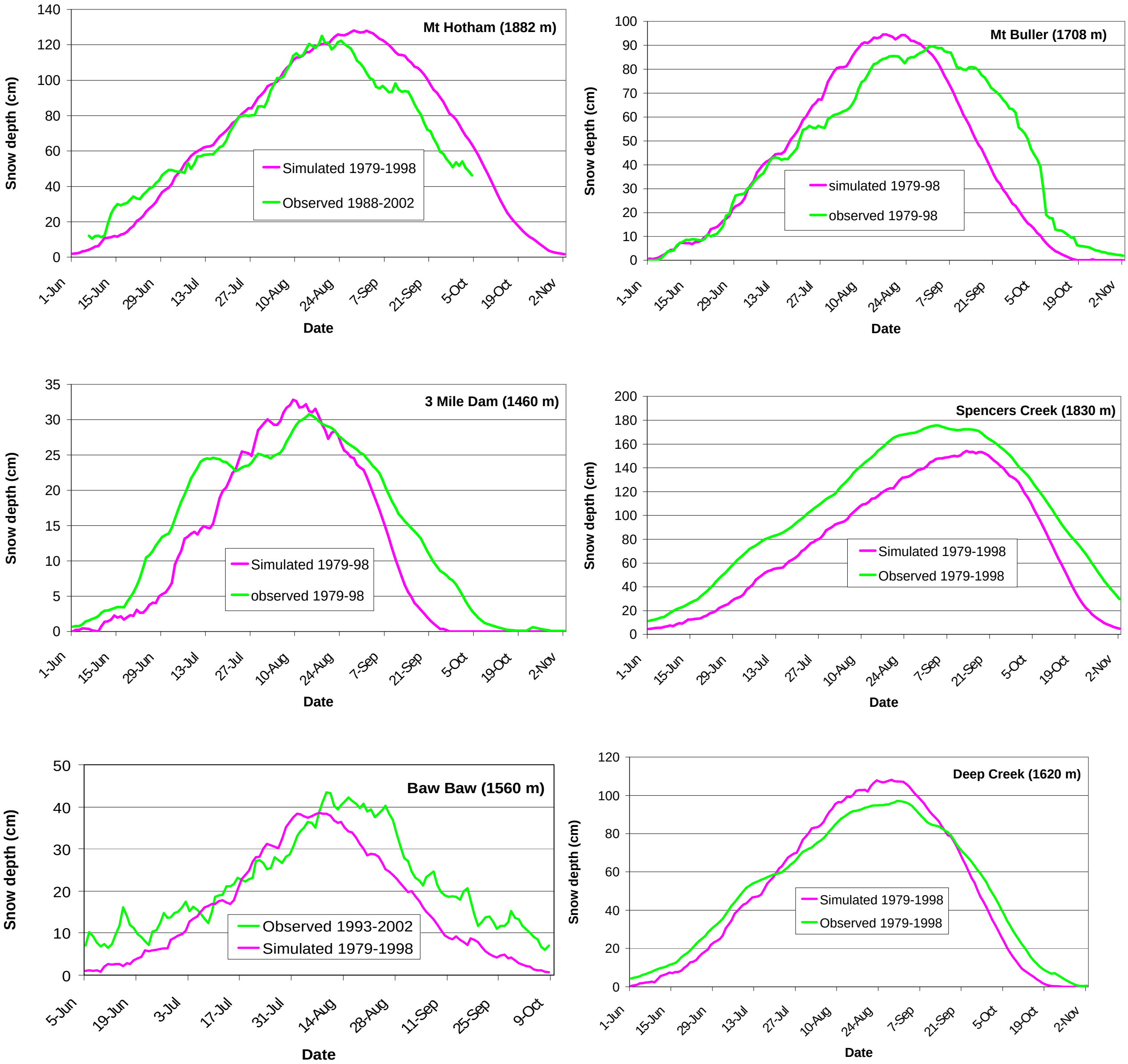

Figure 2-A1: Comparison of simulated and observed snow depths at Mt Hotham, Mt Buller, Three Mile Dam, Spencers Creek, Mt Baw Baw and Deep Creek.

However, at Mt Baw Baw, Lake Mountain and Mt Wellington in southern Victoria, average snow depths and season-lengths were underestimated. This could be due to problems with the input climate data (temperatures too high and/or precipitation too low) and/or a deficiency in the snow model at low elevations. The latter is unlikely since the model performs well at low elevations in New South Wales (e.g. Three Mile Dam). Closer investigation revealed that, while the ANU-derived temperature values were realistic, the ANU-derived precipitation was not increasing with elevation as much as expected in this region, and temperatures may be too high. The most likely reason is the sparsity of high-elevation measurements contributing to the data network in southern Victoria. In addition, it was also considered likely that the monthly temperature data used in the snow model to estimate the proportion of precipitation falling as snow would not operate as accurately in the southern Alps as opposed to the region as a whole. Sensitivity tests indicate that the observed snow profiles at Mt Baw Baw and Mt Wellington were well simulated when the ANU-derived precipitation data were increased by 20% and when the temperature data were lowered by 0.5^{o}C. The Lake Mountain profile was more realistic when ANU-derived precipitation data were increased by 20% and when the temperature data were lowered by 1.0^{o}C. ANU and CSIRO are seeking records of high-elevation weather data in southern Victoria so that the ANU precipitation grid can be improved. In the meantime, for the purposes of this study we have applied the precipitation and temperature corrections above so that the simulated snow profiles are more realistic at Mt Baw Baw, Mt Wellington and Lake Mountain.

Appendix 2 Intergovernmental Panel on Climate Change (IPCC) scenarios of global warming

The IPCC (2001a) attributes most of the global warming observed over the last 50 years to greenhouse gases released by human activities. To estimate future climate change, the IPCC (2001a) has prepared forty greenhouse gas and sulfate aerosol emission scenarios for the 21st century that combine a variety of assumptions about demographic, economic and technological driving forces likely to influence such emissions in the future. They do not include the effects of measures to reduce greenhouse gas emissions such as the Kyoto Protocol.

Each scenario represents a variation within one of four 'storylines': A1, A2, B1 and B2. The experts who created the storylines (described below) were unable to arrive at a most likely scenario, and probabilities were not assigned to the storylines.

A1 describes a world of very rapid economic growth in which the population peaks around 2050 and declines thereafter and there is rapid introduction of new and more efficient technologies. The three sub-groups of A1 are fossil fuel intensive (A1FI), non-fossil fuel using (A1T), and balanced across all energy sources (A1B).

The A2 storyline depicts a world of regional self-reliance and preservation of local culture. In A2, fertility patterns across regions converge slowly, leading to a steadily increasing population and per capita economic growth and technological change is slower and more fragmented slower than for the other storylines.

The B1 storyline describes a convergent world with the same population as in A1, but with an emphasis on global solutions to economic, social and environmental sustainability, including the introduction of clean, efficient technologies.

The B2 storyline places emphasis on local solutions to economic, social and environmental sustainability. The population increases more slowly than that in A2. Compared with A1 and B1, economic development is intermediate and less rapid, and technological change is more diverse.

The projected carbon dioxide concentrations for the various scenarios are shown in Figure 1-A2.

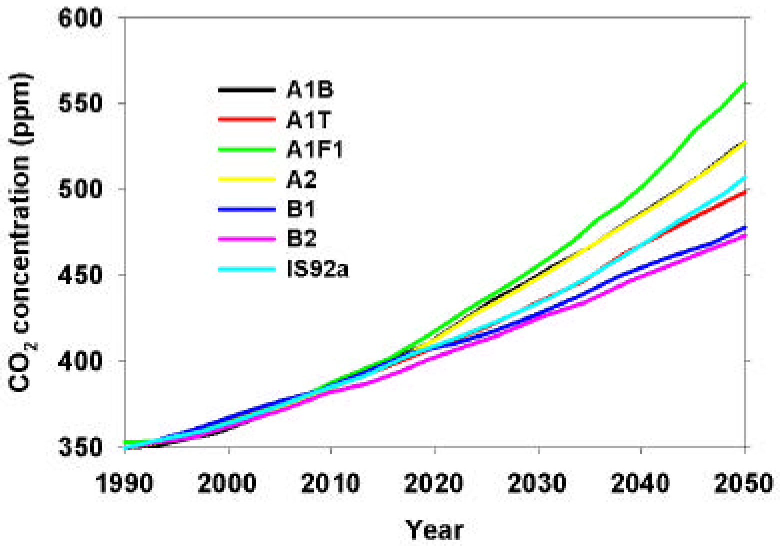

Figure 1-A2: IPCC (2001a) projected concentrations of carbon dioxide (CO_2) for the A1, A2, B1 and B2 storylines. IS92a is a mid-range scenario from the IPCC's previous assessment in 1996. Units are parts per million (ppm).

By incorporating these changes in gas and aerosol concentrations into computer models of the Earth's climate, the IPCC (2001a) has estimated a global-average warming of 0.7 to 2.5^{o}C by the year 2050 (Figure 2-A2) and 1.4 to 5.8^{o}C by the year 2100. The analysis allowed for both uncertainty in projecting future greenhouse gas and aerosol concentrations (behavioural uncertainty) and uncertainty due to differences between models in their response to atmospheric changes (scientific uncertainty).

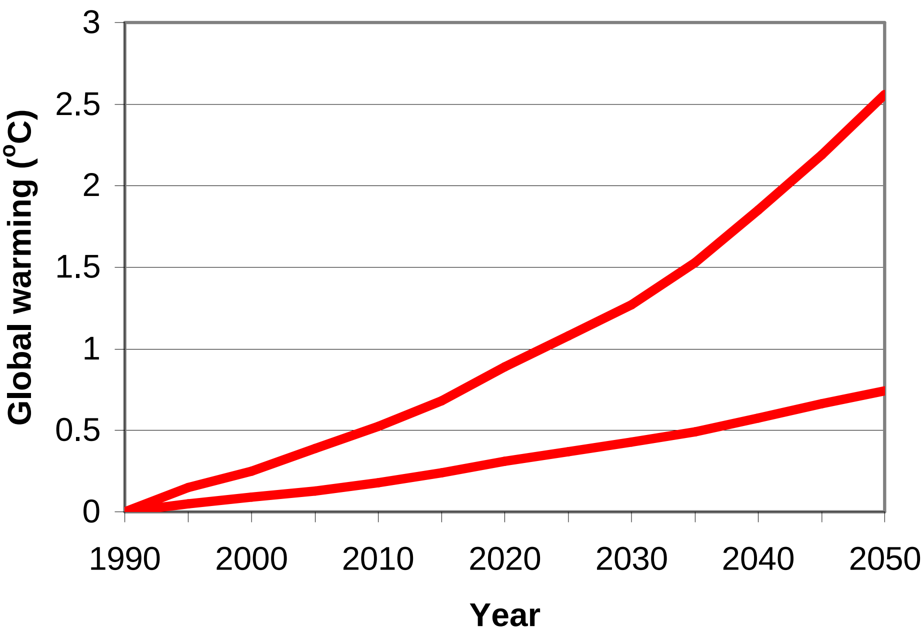

Figure 2-A2: IPCC projected range of global-average warming relative to 1990.

Climate simulations indicate that warming will be greater near the poles and over the land, and that global-average rainfall will increase. More rainfall is predicted nearer the poles and in the tropics, and less rainfall is expected in the middle latitudes such as southern Australia.

Carbon dioxide, and other greenhouse gases such as methane and nitrous oxide, have a lifetime of many decades in the atmosphere. About 50% of the carbon dioxide emitted is absorbed by the ocean and terrestrial biosphere, leaving about 50% in the atmosphere. Greenhouse gas emissions have been growing since 1750, so atmospheric concentrations of these gases have been rising. Even if emissions were held constant from today, concentrations in the atmosphere would continue to rise for decades due to the long lifetime of greenhouse gases. The IPCC has concluded that it is unlikely that concentrations can be stabilized at present levels. In order to stabilize concentrations at a higher level than present, and eventually stabilize the world climate at a warmer level, emissions must be significantly reduced. For example, to stabilize carbon dioxide concentrations at 550 ppm by the year 2120 would require a halving of current emission rates by 2100 and would result in global warming of 1.5 to 2.9^{o}C (O'Neill and Oppenheimer, 2002).

Uncertainties and confidence levels

As shown in Figure 2-A2, the range of uncertainty in projections of global warming increases with time. Half of this range is due to uncertainty about human socio-economic behaviour, and consequent emissions of greenhouse gases and sulfate aerosols. The other half of the range is due to different climate model responses to these scenarios of greenhouse gases and sulfate aerosols. Each of the models is considered equally reliable.

It is important to note that at present, it is not possible to assign probabilities to values within these ranges. However, the IPCC (2001b) defined confidence levels that represent “the degree of belief among the authors in the validity of a conclusion, based on their collective expert judgment of observational evidence, modeling results and theory that they have examined”. The confidence levels are:

- Very high (95% or greater);
- High (67-94%);
- Medium (33-66%);
- Low (5-32%);
- Very low (4% or less).

For the global warming data in Figure 2-A2, we have very high confidence that the lower warming limits will be exceeded and that the higher limits will not be exceeded.