

The Potential Impacts of Climate Change on Victorian Alpine Resorts

A Report for the Alpine Resorts Co-ordinating Council

ACE CRC
ANTARCTIC CLIMATE & ECOSYSTEMS
COOPERATIVE RESEARCH CENTRE

Antarctic Climate & Ecosystems Cooperative Research Centre
Climate Science for Australia's Future

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The ACE CRC is a unique collaboration between the Australian Antarctic Division, the Bureau of Meteorology, CSIRO, the University of Tasmania, the Australian Government's Department of the Environment, the Alfred Wegener Institute for Polar and Marine Research (Germany), and the National Institute of Water and Atmospheric Research Ltd (New Zealand) and a consortium of supporting partners. It is funded by the Australian Government's Cooperative Research Centres Programme.

DISCLAIMER

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DEFINITION OF TERMS AND ABBREVIATIONS USED IN THIS REPORT

CCAM

The Conformal Cubic Atmospheric Model (CCAM) is the regional climate model used to generate the Climate Futures for the Australian Alps projections. It was developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

Climate projections

A climate projection is a model-derived description of possible future climates under a given set of plausible scenarios of climate forcings (any influence on the climate that originates from outside the climate system itself). Climate projections differ from climate predictions because they depend on the emission/concentration/radiative forcing scenario used. Such scenarios are based on assumptions about future socio–economic and technological developments that are subject to substantial uncertainty. A projection is therefore a probabilistic statement of what could happen if certain assumed conditions prevail in the future.

CMIP5 archive

The Coupled Model Intercomparison Project phase 5 archive. The CMIP5 archive includes a standard set of model simulations that have been assessed as providing plausible projections of future climate change. Models admitted to the CMIP5 archive informed the IPCC's Fifth Assessment Report.

Emissions scenarios (RCP8.5)

In the Fifth Assessment Report (AR5), the IPCC addressed the uncertainty about future rates of greenhouse gas and aerosol emissions using Representative Concentration Pathways (RCPs). The four RCPs (2.6, 4.5, 6, and 8.5 W/m2) represent alternative greenhouse gas concentration trajectories resulting from different climate policies.

Reported in this study is the high emissions scenario (RCP 8.5), which does not include any mitigation target, resulting in considerable increases in greenhouse gas emissions and concentrations over time, and a radiative forcing of 8.5W/m2 at the end of the century. RCP8.5 projects increases in global mean temperatures of 2.6–4.8°C for 2081-2100 (relative to 1986-2005). Over the past decade, global emissions have tracked the higher end of the RCP8.5 pathway.

The RCPs replace the Special Report on Emissions Scenarios (SRES) used in previous Assessment Reports. The emissions scenario used here, RCP 8.5, is fairly consistent with the highest SRES (A1FI), although median temperatures rise more slowly during 2035–2080, and faster during other periods in RCP8.5. RCP8.5 projects a similar acceleration in temperature to SRES A2, although median temperatures are consistently higher in the RCP8.5.

Host models

The Global Climate Models used in this study were ACCESS-1.0, CCSM4, CNRM-CM5, GFDL-CM3, MPI-ESM-LR and NorESM1-M. The range in projected changes across the six models is presented in Part II to indicate a range of plausible futures under climate change.

IPCC

The Intergovernmental Panel on Climate Change is the leading international body for the assessment of climate change. The IPCC releases Assessment Reports, which give an up-to-date overview of the current state of scientific knowledge about climate change.

Baseline and Future time periods

In Part I of this report the projected change in precipitation, snow cover and temperature are calculated between the means of the baseline period (1961-1990) and the end of century (2070-2099). 30-year periods are used to incorporate the yearly and decadal variability that is natural in the climate system, for example, during droughts or cool seasons. In Part II we also present results for decadal periods relevant to management decisions.

LaP

The Landscapes and Policy Research Hub (http://www.nerplandscapes.edu.au/) was a multi-disciplinary research hub funded through the Australian Government's National Environmental Research Program. The Climate Futures for the Australian Alps projections were carried out by the Climate Futures Group as part of the LaP research.

Multi-model mean

Some results are presented in this report as the average of six climate models. This approach is commonly used in climatology to provide a 'central estimate' of the projections. Since all climate models admitted to the CMIP5 archive are considered to represent plausible representations of possible futures, a range of climate models are used to incorporate the uncertainty due to the range in climate models.

More information about climate models and climate change can be found in the Synthesis Report Summary for Policy Makers from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, available from http://www.ipcc.ch/report/ar5/syr/ (IPCC 2014b)

Contents

Executive summary

Australia has experienced warming of 0.1°C per decade since 1950 (Nicholls and Collins 2006), and this trend is projected to continue and increase as climate change continues (IPCC 2014). Several studies have investigated the impact of this warming on snow cover and the ski industry. Twenty-five years ago, Ruddell et al. (1990) reported a decline in snow depths at several Australian alpine resorts, and similar results have been documented since by various authors. A recent report focussing on Victoria demonstrated that maximum snow depths have declined and the snow season has finished earlier as temperatures have increased across Australia (Bhend et al. 2012). This trend has been attributed to human influences on the climate (Bindoff et al. 2013), and is expected to increase under continuing climate change (CSIRO and Bureau of Meteorology 2015).

This report outlines a study designed to investigate the potential impacts of ongoing climate change on the Victorian alpine resorts. Part I of the report, "The Impact of Investing in Snowmaking", includes:

1. A review of Australian and international research into the economic viability of snow-making under climate change; and
2. An assessment of the viability of snow-making in relation to its impact on visitor numbers, based on work carried out by Dr Lee, Dr Iftekhar and Prof Tisdell as part of The Landscapes and Policy (LaP) Hub (http://www.nerplandscapes.edu.au/);

Part II of the report, "Climate change in the Australian Alps region", includes:

1. An overview of the changes projected to occur in mean temperature, precipitation, and snow over the Australian Alps region, with new regional insights from the new Climate Futures for the Australian Alps projections;
2. An assessment of the changes projected to occur in temperature, precipitation and snow cover, between the baseline (1961-2010) and end of century (2070-2099) time periods, at each of the six Victorian alpine resorts (Falls Creek, Lake Mountain, Mt Baw Baw, Mt Buller, Mt Hotham and Mt Stirling);

3. An assessment of shifts in the timing and duration of the ski season based on natural snowfall; and

4. An analysis of variability in snowmaking conditions and changes in the frequency of suitable snowmaking conditions under future climate conditions.

Summary of Part I: The Impact of Investing in Snowmaking

1.0 Review of literature relevant to assessing the economic viability of snow-making under climate change

The potential impact of climate change on alpine resorts has received extensive attention in recent decades, focusing on the supply side (climatic constraints on natural snow and snow-making conditions), as well as the demand side (visitor response) and the cost of snow-making operations and infrastructure. Several studies have shown that snow-making has an important role to play as alpine resorts adapt to declining natural snow cover around the world.

Some consistent messages emerge from the review of the literature:

- There is overall consensus around the world that natural snow cover and depth will continue to decline and the length of the ski season contract further as the climate warms;
- Smaller resorts, those at lower altitudes, and those with inadequate snow-making facilities will be the most vulnerable to climate change;
- Snow-making is expected to sustain the ski industry in many regions until the middle of this century using current snow-making technologies;
- By mid-century there will be less natural snow and a significantly increased need for snowmaking at the same time as snow-making opportunities will decline. This may lead to shorter and less reliable ski seasons;
- The economic costs of snow-making are expected to rise as natural snow cover declines, melting and evaporation rates increase and water and electricity costs rise. More snow will need to be made at warmer temperatures, particularly at the beginning of the ski season, at greater costs (Scott et al. 2007)(Scott et al. 2007);
- The economic viability of snow-making into the future will be determined by the extent of natural snow cover decline and the cost of snow-making required to sustain the ski season. The ability of alpine resorts to absorb rising costs will depend strongly on visitor perceptions of climate change and their responses to declining and less reliable natural snow cover.

2.0 The relationship between visitor numbers and snow depth at Victorian alpine resorts

Researchers with the Landscapes and Policy (LaP) research hub (http://www.nerplandscapes.edu.au/) investigated the relationships between natural snowfall, snowmaking and visitation rates at six resorts in Victoria, Australia, over a sixteen year period (1997 to 2012). This research is extended here to include the years 2013-2014, and new results are presented to highlight the relationship between visitation and snow depth at individual resorts. The results provide information to support decisions about future investment in snow making infrastructure.

The results show that:

- Visitors to the Victorian alpine resorts are responsive to changes in snow conditions;
- On average, the number of visitors increases with maximum snow depth, both natural and artificial, and they stay for longer. For an increase of 1cm in natural snow, there was an increase of 110 visitors (1.8% increase) and 187 more visitor-days (1.6% increase) across all resorts;
- Similar increases were associated with increases in snow in the artificial snow-making areas (102 more visitors (1.6% increase) and 181 more visitor-days (1.5% increase));
- Visitor response differs at different resorts, with the higher altitude resorts (Mount Buller, Falls Creek and Mount Hotham) showing the greatest increases in visitor numbers and duration of stay with increased snow depth (both natural and artificial). Mount Buller, with 191 visitors per cm of snow and 338 visitor days per cm of snow, gains the most from increases in snow depth. Mount Stirling was the least responsive to changes in snow depth (28 visitors per cm; 55 visitor days per cm).
- The Lake Mountain resort is highly sensitive to maximum snow depth, with 200 more visitors and 215 more visitor days associated with a 1cm increase in natural snow;
- All resorts recorded positive growth in visitor numbers and visitor-days between 1997 and 2014.
- Variability in visitation varied less across years than across resorts, but in certain years, such as 2006, visitor numbers and snow depth were particularly low;
- Snow-making did not substantially alter the relationship between snow cover and visitation, but it did reduce the inter-annual variability in visitor numbers by a third;
- Visitors are more responsive to changes in natural snow depth than to changes in artificial snow depth when resorts and years are considered separately. This suggests there may be opportunities to increase potential visitors' understanding of the extent of current snow-making and its success in maintaining reliable skiing conditions.

Summary of Part II: Climate change in the Australian Alps region

3.0 Changes in climate projected for the future in the Australian Alps region

The Climate Futures for the Australian Alps projections provide regional details of climate change between the baseline period (1961-1990) and the end of the century (2070-2099). They show that, by the end of the century, under a high emissions scenario (RCP 8.5):

- Average temperatures across the Australian Alps could increase by 4-5°C;
- Annual precipitation may decrease by 0-20%;
- Snow cover and volume will decline to the extent that eventually only the highest peaks (such as Mt Perisher and Falls Creek) will experience any snow;
- These changes vary seasonally and across the south east Australian region, influenced by elevation, aspect and distance from the coast.

These changes in climate are likely to have significant consequences for natural ecosystems and recreational use across the Alps region.

3.1 Changes projected to occur at the Victorian Alpine Resorts between current and future time periods

The results show that by the end of the century (2070-2099), relative to recent decades (1961-2010), under the high emissions scenario (RCP 8.5) considered here:

- There is an increase of approximately 4°C in mean temperature at all resorts;
- There is an increase in the number of extreme hot days and a decrease in the number of very cold days at all resorts;
- The coldest Winter temperatures increase by 2.5 to 7°C;
- The hottest Summer days are approximately 5°C warmer in the future;
- On average, Falls Creek is projected to experience the greatest decline in annual precipitation (-14%, model range -23% to 0%), followed by Lake Mountain (-13%, model range -20% to -3%), Mt Baw Baw (-11%, model range -19% to -2%) and Mt Hotham (-11%, model range -20% to +3%). Mt Stirling and Mt Buller are projected to have the lowest decline in precipitation (-7%, model range -13% to +6%);
- All models at all resorts project decreased Winter precipitation;
- Snowfall declines substantially at all resorts, with mean annual snowfall decreasing from between 60% and 80%. Falls Creek shows the largest decline in snowfall (-79%, model range -85% to -72%), followed by Mt Baw Baw (-78%, model range -81% to -76%), Mt Buller (-74%, model range -86% to -70%) and Mt Stirling (-74%, model range -86% to -67%), Mt Hotham (-71%, model range -86% to -63%) and then Lake Mountain (-59%, model range -69% to -35%).

3.2 Shifts in the timing and duration of the ski season based on natural snow

Consistent with observations, model projections indicate a steady reduction in snow depth across all resorts over recent decades. A contraction in the duration of the ski season is shown, with a later start and earlier finish relative to the modelled historical period (1960's). The length of the ski season has contracted by 17% to 28% across the resorts over recent decades, and is projected to contract by 65% to 90% by the 2070 period relative to 2000-2010. Projections show the greatest contraction in season length at Mt Stirling and Mt Buller, and the lowest contraction at Mt Baw Baw and Falls Creek.

3.3 Changes to the frequency of suitable snowmaking conditions under future climate conditions

As natural snow declines, more snow will need to be made, under warmer conditions, to achieve the target snow depth profiles throughout the season. The number of hours suitable for snowmaking before the start of the ski season (June 3rd) is projected to decline substantially at all resorts. There is a gradual decline from 1960 to 2000, superimposed on large year-to-year variability, followed by a marked drop in available hours for snowmaking between the 2020's and 2030's. Relative to the 2010's, opportunities for snowmaking are halved by 2030 at all resorts, with the exception of Falls Creek where opportunities halve by the 2040's.

However, if snow is made at warmer temperatures, opportunities for snowmaking may be able to be maintained at current (2010) levels until the 2030's (-1°C wet bulb temperature), or until 2080-2090 if snow can be made at -0.5°C wet bulb temperature. However, making snow at warmer temperatures may be associated with trade-offs in cost and quality of snow.

The new projections confirm previous research by CSIRO that demonstrated reductions in natural snowfall and contractions in season length based on both natural snow and opportunities for artificial snowmaking (Whetton et al. 1996, Hennessy et al. 2008, Bhend et al. 2012). In line with previous work, the current work suggests that climate change impacts are not only a challenge for the future, but are already impacting the Victorian alpine resorts.

The future viability of skiing at the alpine resorts will rest on the ability to make snow, but by 2020-2030 conditions suitable for snowmaking are projected to decline substantially, and the costs of making more snow under warmer conditions are likely to continue rising.

Part I: The Impact of Investing in Snowmaking

1.0 Review of literature relevant to assessing the economic viability of snow-making under climate change

The potential impact of climate change on snow-making has been a focus of research since the 1980’s, with studies of the impact of climate change on natural snow depth and potential for snow-making in Canada, the US, the European Alps, Sweden, New Zealand and Australia (Table 1.1). Several studies have shown that snow-making has an important role to play as alpine resorts adapt to declining natural snow cover around the world.

Table 1.1 summarises the literature relevant to assessing the economic viability of snow-making under climate change. It is not an exhaustive list, but includes all peer-reviewed Australian literature and an overview of the international literature that investigates near to mid-term projections of change (up to 2050) using robust techniques.

There is overall consensus around the world that natural snow cover and depth will continue to decline and the length of the ski season contract further as the climate warms. However, studies that consider snow-making generally report lower impacts of climate change on alpine resorts than those that only consider natural snow (marked with an asterisk in Table 1.1). In many cases, snow-making is expected to sustain the ski industry until the middle of this century using current snow-making technologies (Steiger, 2010). Snow-making is likely to continue to guarantee season starts, extend the season duration, and maintain the viability of lower altitude slopes in the short term. Nevertheless, by mid-century there will be less natural snow and a significantly increased need for snowmaking at the same time as snow-making opportunities are declining. This will lead to shorter and less reliable ski seasons, with the early part of the ski season being identified as being particularly at risk (Scott et al. 2012). The literature suggests that there will be a contraction in the number of ski areas, particularly at lower altitudes. It has been estimated that the snowline will rise by 150m per 1°C of warming (Abegg et al. 2007). The aspect and slope of individual runs will also influence rates of change and the viability of snow-making.

The economic costs of snow-making are expected to rise non-linearly as natural snow cover declines, melting and evaporation rates increase and water and electricity costs rise (Agrawala 2007). As temperatures increase, more snow will need to be made at warmer temperatures, particularly at the beginning of the ski season, at greater costs (Scott et al. 2007). The economic viability of snow-making into the future will be determined by the extent of natural snow cover decline, which will depend on regional climate change, and the cost of snow-making required to maintain sufficient snow cover to sustain the ski season. The ability of alpine resorts to absorb rising costs will depend strongly on visitor perceptions of climate change and their responses to declining and less reliable natural snow cover.

The interaction between reduced snow cover and visitor perceptions and behaviour has recently received increased attention. The Organisation for Economic Co-operation and Development (*OECD*) published a detailed report in 2007 on climate change adaptation options in alpine resorts across Europe (Agrawala 2007). This report provides detailed overview of technological, behavioural and financial adaptation options, as well as reviews of recent research into visitor perceptions of climate change and response to declining and variable snow cover.

Four Australian studies are of particular relevance to the Victorian alpine resorts. Hennessy et al. (2008) assessed recent changes in temperature and snow cover across the Australian alpine region and estimated changes in natural snow cover and depth for 2020 and 2050 using a pattern scaling approach and the CSIRO snow model (Whetton et al. 1996). They also assessed the extent to which snow-making may be able to offset reduced natural snow cover.

Their results showed that temperatures have increased 0.2°C per decade during the period 1962 to 2001 at alpine sites at altitudes of 1380-2000m. Maximum snow depth declined over a similar period at several resorts in NSW (Three Mile Dam, Rocky Valley Dam and Spencers Creek), but the trend was not statistically significant, due to the very high inter-annual variability that is typical for the region. The projections suggested that by 2020, the total area with at least one day of snow cover per year could decrease by 10-39%, and the average ski season length could be reduced by 5-50 days. This represents a contraction of season length of 10-60% at lower altitude resorts such as Mt Baw Baw and 5-30% at sites above 1600m, such as Mt Hotham. By 2050, snow cover was projected to decline by 22-85% and ski season length by 15-99%. The wide range in values is caused by the differences between individual resorts, and the climate change scenario chosen. Here the low impact scenario represents the lowest projected temperature increase and the greatest precipitation increase (ie. relatively cool and wet, change of +0.2°C and +0.9% precipitation), and the high impact scenario represents the highest temperature increase and greatest precipitation decrease (ie. relatively warm and dry, change of +1.0°C and -8.3% precipitation).

They compared the average number of hours suitable for snowmaking now and under future climate conditions at seven alpine resorts, including Mt Buller, Lake Mountain, Mt Baw Baw and Falls Creek, based on the assumption that snow making requires wet bulb temperatures below -2°C. They found that the average number of hours suitable for snowmaking declined by 2-7% under the low impact scenario and by 17-54% under the high impact scenario. Fewer snowmaking hours meant that the volume of snow that could be made using two different snow guns (the names of which were withheld for commercial reasons) was reduced by 3-10% under the low impact scenario and by 18-55% under the high impact scenario.

The CSIRO snow model was also used to simulate the amount of snow that would need to be made to maintain the target snow profiles at six alpine resorts into the future. The target snow profile describes the amount of snow required at particular times of year to ensure the successful long-term operation of each resort. The results show that 11-27% more snow guns would be required by 2020 to reach the target snow profile under the low impact scenario, and 71-200% under the high impact scenario. These values equate to increases in total snow volume made of 5-17% and 23-62% for the low and high impact scenarios respectively. The study concluded that “with sufficient investment in snow guns, the Australian ski industry may be able to manage the effect of projected climate change on snow cover until at least 2020.” (Hennessy et al. 2008 pg 255).

The authors acknowledge that the study could be improved with daily data to improve within and between year variability in snow cover and estimates of the proportion of precipitation falling as snow. Additionally, only mean temperatures were available from the climate models they used, which may have underestimated the frequency of temperatures cold enough for snowmaking, but also the rate of melting and evaporation. Using daily minimum and maximum temperatures could help further refine the results.

Pickering & Buckley (2010) used the calculations of changing natural snow volume, snow-making requirements and snow gun specifications from the Hennessy (2008) study to calculate the economic cost of snow making required to offset the reductions in natural snow that are projected to occur by 2020. Using publically available data, they estimated that the six resorts they considered (Mt Perisher, Mt Thredbo, Mt Selwyn, Mt Buller, Falls Creek, and Lake Mountain) would need to install 1.7-45 more snow guns per run, and increase total water consumption by 23-62% per run to sustain the same total snow cover as is currently achieved. Overall, 726 more snow guns would be required by 2020, at a cost of US $95.2 million (calculated in 2008 dollars). They also considered the environmental constraints on snowmaking in Australia under a changing climate, and highlighted water availability, electricity demand and impacts on natural systems as factors that may limit snowmaking potential in the future (Pickering and Buckley 2010).

In 2007, Pickering & Buckley (2010) repeated a survey by König (1998) which assessed skier attitudes towards climate change. Ninety percent of the skiers surveyed at the Perisher Blue resort in NSW (of a sample of 351) said that they would ski less often (69%), not at all (5%), or overseas (16%) if the next five years had low natural snow. This had increased from 75% of skiers who answered the same questions in 1996. These numbers are high compared to a similar survey done in Switzerland in 1996-1997, which found that only 36% of skiers would ski less often or stop skiing if the next five years had low snow (Behringer et al. 2000). The authors suggest that the higher sensitivity of Australian skiers to low snow may reflect the more restricted opportunities for skiing in Australia compared to other regions around the world, and the response of Australian skiers might be more similar to skiers at smaller resorts in Europe, who have been shown to be more sensitive to low snow cover (Hughes 2011). Almost 80% of those surveyed in 2007 believed that climate change would have a detrimental effect on the Australian ski industry, with 59% believing this would occur before 2030 and 25% before 2060.

Unfortunately, the relevance of this study is limited by the fact that it did not consider skiers' attitudes to snow-making. Attitudes towards snow-making may well change as natural snow declines, as shown by Putz et al. (2011), who found that snowmaking is being increasingly accepted among tourists. Further, surveys of visitor intentions often over-estimate expected responses, and do not always reflect actual visitation numbers (Scott et al. 2012). Studies of actual visitation rates in low snow years generally forecast a less pessimistic future for skier demand under changing climate conditions (Dawson et al. 2009), as is shown in the next study by Pickering (2011).

The final study relevant to Australian snow conditions and snow making potential is that by Pickering (2011), who compared visitation patterns at the six Victorian alpine ski resorts using an analogue climate-year technique. This approach compares visitation patterns observed in a relatively warm and dry year, 2006, considered to represent projected future climate conditions, with those recorded in 2007, a year more typical of current climate conditions. The study also used linear regression to investigate the relationship between natural snow depth and visitation patterns over time. Analyses were based on publically available data from the 'End of Season Reports' published by the Alpine Resorts Co-ordinating Council (ARCC) (http://www.arcc.vic.gov.au/publications-and-research/). However, these data did not enable in-depth analyses of snow depth from individual resorts prior to 2006, so this relationship was based on snow depth data from Spencers Creek and annual visitation data from 1997-2007.

The study found that across all resorts, natural snow cover in 2006 was 80% less than that recorded in 2007, and the duration of the ski season was not long enough to be considered viable (where 60-70 days minimum days of operation is considered necessary for a viable season, and a minimum snow depth of 30cm natural snow or a more conservative >20cm is required for operation). Snowmaking was found to be effective at extending the ski season, in both good and bad years, but was particularly important in 2006, when natural snow cover was low. In 2006, snow making increased the number of days with snow cover greater than 30cm from 32 to 105 days at Falls Creek; 0 to 75 days at Mt Buller; 35 to 94 days at Mt Hotham; and 0 to 32 and 70 days at Lake Mountain and Mt Baw Baw respectively (Pickering 2011). The three lowest resorts were therefore only able to open in 2006 because of snow making.

However, despite the season being extended by snow making in 2006, visitation numbers were still low. Thirty-eight percent fewer visitors were recorded in that year, compared with the average of the previous nine years. On the other hand, the average duration of stay was 32% longer. Different visitor responses to low natural snow cover were observed at different resorts. The lower altitude resorts were most susceptible to low snow, with average numbers of visitors reduced by 52-86% in 2006 compared to the preceding nine years. Of the higher altitude resorts, Mt Buller was the most impacted, with a reduction of 24%, while Mt Hotham recorded an increase of 10% in visitor numbers. The author suggests that this may be due to skiers moving from the low altitude resorts to Mt Hotham, and then staying longer at the higher altitude resort. Changes in operating costs and visitation rates in the low snow year of 2006 led to substantially lower profits at Mt Hotham, while operating losses were reported at all other resorts with the exception of Lake Mountain (Pickering 2011, citing Alpine Resort Management Board annual reviews 2007). While snow making offset some of the declines in visitor numbers resulting from low natural snow, it did not fully negate the effect. The impact of consecutive warm years on visitor numbers also remains uncertain.

The relationship between the number of visitor days and snow cover at Spencers Creek between 1997 and 2007 is presented for each of the six Victorian resorts (Pickering 2011, pg 776). Statistically significant results were found for all of the resorts except Falls Creek, and the strength of the relationship varied between the resorts. At Mt Baw Baw, snow cover explained 36% of the annual variation in visitor days, while at Mt Buller the relationship was stronger, with snow cover explaining 78% of the variation in visitor days. The slope of the regression also differed at different resorts. The increase in visitor days with increased snow cover was greatest at Mt Buller (1581 more visitors per extra metre day of snow) and lowest at Mt Stirling (480 more visitors).

One of the difficulties in comparing results from different studies is that they frequently use different methods, indices, and time periods and emissions scenarios. For example, in the last Pickering study, the year 2006 was used to indicate a potentially typical year under future climate change. The annual average temperature recorded across three Victorian resort weather stations in 2006 was 0.6°C above long-term averages (Pickering 2011). This is at the lower end of the range projected to occur by 2030, which is 0.6-1.3°C, annually averaged over all emissions scenarios (because the uncertainty due to emissions scenario is low at this short time-scale) (CSIRO and Bureau of Meteorology 2015). The change in precipitation in 2006 was -48%, which is high compared to the decrease of around 15 per cent that is projected to occur in winter and spring by 2030.

1.1 Conclusion

The potential impact of climate change on alpine resorts has received extensive attention in recent decades, focusing on the supply side (climatic constraints on natural snow and snow-making conditions), as well as the demand side (visitor response) and the cost of snow-making operations and infrastructure. Some consistent messages emerge from a review of the literature. Firstly, there is little doubt that natural snow cover will decline, and snow-making will be an essential adaptive response around the world. Secondly, the European and North American literature identifies smaller resorts, those at lower altitudes, and those with inadequate snow-making facilities to be the most vulnerable to climate change. Beyond these general indications, however, it is difficult to directly apply the results to Australian resorts. The Australian ski industry is quite different to the international ski industry, where snow cover is more extensive and the ski season is longer. Rates of climate change, costs of snow-making, availability of water and energy, and visitor numbers and expectations are all very different in Australia. Region-specific analyses in the Australian Alps have provided valuable information on snow-making requirements and costs under climate change, but a greater understanding of Australian visitor perceptions would improve the ability to predict short and medium-term responses to declining snow and increased snow-making.

Table 1.1: Literature relevant to assessing the economic viability of snow-making under climate change. The asterisk indicates studies that did not consider snow-making

Impacts of climate change on natural snow cover and potential for snow-making (Supply side analyses)		
Country	Reference	Conclusions
Australia	(Galloway 1988)	Duration of snow cover halved with a 2°C increase in temperature, and projected increases in precipitation did not offset the effect of warming.*
	(Whetton et al. 1996)	Substantial declines in snow cover by 2030 under the 'worst-case' scenario (+2°C and -10% precipitation), but snow cover maintained at high altitude sites under the 'best-case' scenario (+0.5°C and +10% precipitation).*
	(Hennessy et al. 2008)	Ski season length decreased by 10-60% by 2020, and 15-99% by 2050. An increase of 11-27% in the number of snow guns required under the low impact scenario (+0.2°C and +0.9% precipitation), and 71-200% under the high impact scenario (+1°C and -8.3% precipitation). See text for more details.
	(Bhend et al. 2012)	Declines in snow cover and maximum snow depth across Victorian resorts. Average snow season 5-35 days shorter by 2020 across Falls Creek, Mt Hotham, Mt Buller and Mt Buffalo under three scenarios. Trends will be superimposed on large natural year-to-year variability. Larger changes likely at lower elevations (eg. Mt Baw Baw and Lake Mountain).*
	(Hendrikx et al. 2013)	By the 2040s, a decline of 57-78% of the current maximum snow depth at two sites in the Snowy Mountains, NSW. At low altitudes, days with >30cm snow decrease from 94-155 days currently to 81-114 days.*
New Zealand	(Hendrikx et al. 2012)	By the 2040s, depending on the climate model used, there is a decrease in snow of 3- 44% at 1,000 m, and a range from + 8% to - 22% at 2,000 m. The elevation at which snow duration exceeds 3 months rises by up to 200m.*
	(Hendrikx and Hreinsson 2012)	By the 2040s, potential snowmaking hours decline to 53-82% of a worst-case year in the 1990s, but sufficient snow could be made to either maintain 1990s levels or to exceed 100 days.
	(Hendrikx et al. 2013)	By the 2040s, a decline of 90-102% of the current maximum snow depth at two sites in the Central Otago region. At low altitudes, days with >30cm snow decrease from 125 days currently to 9-126

		days.*
United States	(Scott et al. 2008) (Dawson and Scott 2013)	Snowmaking investment substantially reduced the vulnerability of the ski industry and climate change posed a risk to only 4 of the 14 ski areas in 2010–2039. Many of the 103 ski areas in the US Northeast not expected to be economically viable as early as mid-century.
Canada	(Scott et al. 2003)	Average ski season projected to decline by 0–16% in the 2020s. Ski areas in southern Ontario could remain operational into the 2020s, but 36-144% increase in snow-making required. An increase of 8-59% in snow-making required by 2020 to maintain an adequate snow base and season length, depending on resort and climate change scenario.
Switzerland	(Koenig and Abegg 1997) (Uhlmann et al. 2009)	65% of Swiss ski fields could maintain snow-reliability** with a 2ºC temperature increase. Visitor numbers in low snow years drop at low altitude resorts, while higher altitude (glacier) resorts benefit.* A large decrease in snow depths and duration, even at high elevations, across all resorts in Switzerland. Altitude, exposure and slope are important determinants.*
Germany	(Endler and Matzarakis 2011)	Reduction in snow days of approx. 40% and up to 25% fewer days suitable for snow-making by 2021–2050.
Austria	(Steiger 2010)	All resorts modelled remain snow reliable until the 2040s (under the A1B scenario) with current snowmaking technology.
European Alps	(Abegg et al. 2007)	Substantial impacts likely across all resorts*, requiring adaptation including snow-making. However, increasing investment, operational and maintenance costs, as well as water, energy and ecological limitations will restrict viability of snow-making.
Visitor responses (Demand side analyses)		
Australia	(König 1998) (Pickering 2011) (Hopkins et al. 2013)	75% of skiers surveyed said they would ski less often if there were 5 consecutive years of low snow cover. See text for more details.* There is a relationship between natural snow depth and visitation patterns at Victorian resorts. Different visitor responses to low natural snow cover observed at different resorts, with low altitude resorts more susceptible. See text for more details.* Perceptions of New Zealand as more snow reliable may influence future domestic demand, but non-

		climate factors also important in determining relative vulnerability to climate change.
United States	(Dawson et al. 2009)	A decrease in visitation of 11- 12% by 2040-69 (medium and high emissions scenario). Small and extra-large ski areas most economically vulnerable to increased snowmaking costs, decreased season lengths and lower visitation rates.
	(Hamilton et al. 2007)	Weather variables and snow depth did have a statistically significant positive effect on downhill ski lift ticket sales.*
Austria	(Steiger 2011)	Skier visits were low in a warm winter, compared to a climatically normal year. Small to medium and low-altitude resorts, and those with insufficient snowmaking facilities, were most affected.
	(Hughes 2011)	The impact of snow depth on overnight stays was low at high altitude resorts with extensive snow-making, but stronger at low altitude resorts, where overnight stays decreased with decreased snow depth.
	(Falk 2010)	A positive relationship between stay duration and snow depth was found at low altitude resorts (<2000m), but not at high altitude resorts. However, the effect was not large, due to extensive snow-making.
Switzerland	(Behringer et al. 2000)	36% of skiers surveyed said they would ski less often or stop skiing if the next five years had low snow.
	(Putz et al. 2011)	Snowmaking is being increasingly accepted among tourists, but a wide range of activities in both winter and summer affects choice of destination.
European Alps	(Abegg et al. 2007)	Declines in snow reliability may be offset in many regions with snow-making, but alternative operational practices, financial instruments and new business models will also be needed.
Japan	(Fukushima et al. 2002)	More than 30% decrease in visitor numbers forecast in almost all ski areas in Japan with a 3°C increase in temperature (no change in precipitation).*
Economics		
Australia	(Pickering and Buckley 2010)	700 additional snow guns needed across Australian resorts by 2020, requiring US $100 million in capital investment, up to 3,300 ML of water per month, and increased energy consumption. See text for more details.
Canada	(Scott et al. 2007)	The economic impact of lost revenue from shortened ski seasons and increased cost of snowmaking is likely to be prohibitive for some ski resorts.

**snow –reliability is defined in Europe as having more than 100 skiable days (snow depth greater than 30cm)

2.0 The relationship between visitor numbers and snow depth at Victorian alpine resorts

Summary

- There is a significant positive relationship between maximum snow depth and visitation patterns at the six Victorian alpine resorts from 1997 to 2014;
- For an increase of 1cm in natural snow, there was an increase of 110 visitors (1.8% increase) and 187 more visitor-days (1.6% increase) across all resorts;
- Similar increases were associated with increases in snow in the artificial snow-making areas (102 more visitors (1.6% increase) and 181 more visitor-days (1.5% increase));
- Snowmaking substantially reduced the inter-annual variability in visitation number, by 33%;
- The impact of changes in snowfall is not the same at all resorts. The high altitude resorts (Mount Buller, Falls Creek and Mount Hotham) attract more visitors per season, and visitors stay for longer in these resorts if there is additional snowfall;
- The Lake Mountain resort is highly sensitive to maximum snow cover, with 200 more visitors and 215 more visitor days associated with a 1cm increase in natural snow.

2.1 Introduction

Snow-making technologies have been widely used in the past to ensure season start dates, extend the end of the season, improve viability of low altitude slopes and boost low-snow years. However, the cost of snow-making is expected to rise substantially as natural snow declines, because more snow will need to be made across larger areas, for longer periods of time, and under more marginal climatic conditions (Agrawala 2007). The ability of alpine resorts to absorb rising costs will be strongly influenced by visitor perceptions of climate change and their responses to declining and less reliable natural snow cover.

Visitor numbers in Australian alpine resorts have been shown to be sensitive to natural snowfall (Pickering 2011) and perceptions of climate change impacts (Pickering et al. 2010), but the impact of snow-making on visitation has not been studied. This has been identified as a major limitation of much of the literature around the world that constrains its usefulness to decision makers. Studies that do not consider snow-making “do not reflect the current operating realities of many ski operations, let alone their adaptive capacity and are of little use to the tourism industry.” (Scott et al. 2012 pg. 217).

Researchers with the Landscapes and Policy (LaP) research hub (http://www.nerplandscapes.edu.au/) addressed this gap by investigating the relationships between natural snowfall, snowmaking and visitation rates at six resorts in Victoria, Australia, over a sixteen year period (1997 to 2012). This research, by Dr Lee, Prof. Tisdell and Dr Iftekhar, is summarised here. The analysis is updated in this report to include the years 2012-2014.

The following research questions were addressed:

1. To what extent are the number of visitors and duration of stay affected by natural and artificial snow depth in the Victorian alpine resorts?
2. Are visitation patterns affected in the same way in different years and across different resorts?

The results are presented here in two forms. Firstly, the Landscapes and Policy hub analysis (hereafter the LaP analysis) is presented, which used linear mixed effects regressions of the relationship between snow depth and visitor numbers and duration of stay. This analysis enables comparisons to be made across years and resorts. Secondly, simple linear regressions of snow depth against visitation are presented for each resort separately, to visualise the relationship at individual resorts.

2.2 Methods

2.2.1 Resorts

Data on snow depth and visitation (visitor number and visitor-days) were provided by the Alpine Resorts Co-coordinating Council (ARCC) for each of the six snow tourism resorts in Victoria: Mt Baw Baw (37°49'59.9"S, 146°15'59.8"E), Lake Mountain (37°30'14.45"S, 145°52'56.3"E), Mt Hotham (36°58'30.0"S, 147°07'55.2"E), Falls Creek (36°51'46.8"S, 147°16'45.9"E), Mt Buller (37°09'15.5"S, 146°29'27.5"E) and Mt Stirling (37°07'51.5"S, 146°29'00.5"E) (Figure 2.1).

Table 2.1: Selected features of snow tourism resorts in Victoria, Australia (ARCC 2012)

Resorts	Highest Altitude (meters)	Altitude lift point		Accessibility		Facilities				Snowmaking	
		Highest	Lowest	Drive time Sydney (day)	Drive time Melbourne (hours)	Lift count	Bed count	Cross country Ski trails (km)	Downhill ski area (Ha)	Area	Number of snow guns
Mt Hotham	1861	1845	1450	1	4.5	13	7000+[1]	30	300	36	75
Mt Buller	1804	1790	1390	1	3	22	7500	9	263	100	81
Falls Creek	1849	1780	1500	1	4.5	15	5100	65	450	100	210
Mt Baw Baw	1564	1560	1450		2	7	700	10	37	10	10
Lake Mountain	1490	1340[2]			2	0	400+[3]	37[4]	0	3	6
Mt Stirling	1749	1340[2]		1	3	0	0	65	0	0	0

Note: 1) including Dinner Plain; 2) Base altitude; 3) Number of beds at Marysville and Triangle area; 4) Groomed Ski trails; 5) Source: Pickering (2011)

The resorts cover a range of elevations and terrain, have different facilities and snowmaking infrastructure, and offer different visitor experiences (Table 2.1). The higher altitude resorts, Mount Buller, Falls Creek and Mount Hotham, receive the majority (70-80%) of ski-field visitors. At these resorts natural snow is both more likely and more persistent, and there is greater capacity for snowmaking. Lake Mountain and Mount Stirling have no downhill ski infrastructure or accommodation, and instead cater to "snow-play" and cross country skiing.

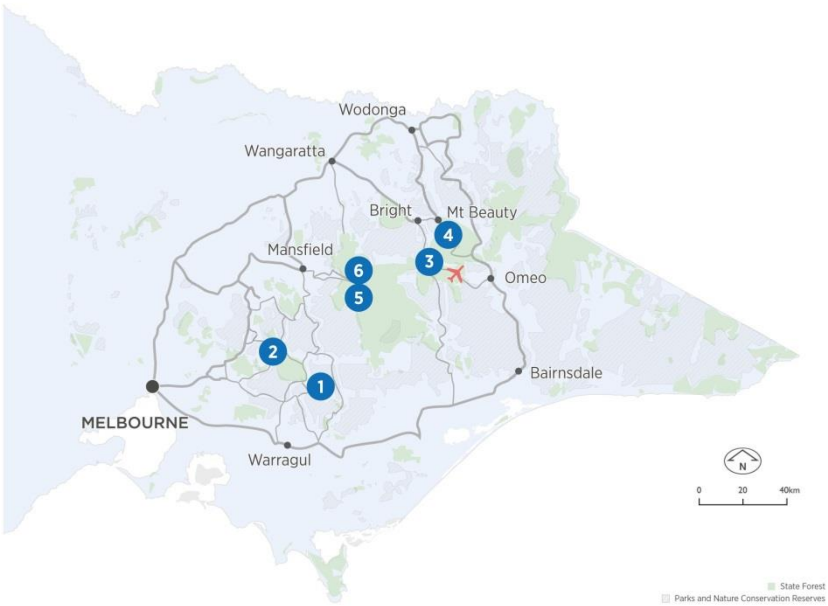

Figure 2.1: Victorian snow tourism resorts and associated road networks. Here: Mt Baw Baw = 1, Lake Mountain = 2, Mt Hotham = 3, Falls Creek = 4, Mt Buller = 5 and Mt Stirling = 6 (Source: ARCC Website)

2.2.2 Visitation records

Visitation responses were available as weekly aggregates of visitor numbers and visitor-days, reported for the 7 days ending on the 18 Sundays of the snow seasons 1997-2014. Records are based on data from automatic counters installed on the access roads to each resort, supplemented by survey data. The counters were installed in different years (eg. Falls Creek 1994; Lake Mountain, 1997; Mount Hotham 2001). A detailed methodology for each resort is provided in http://www.arcc.vic.gov.au/assets/Uploads/research/Summer-Report-2013-2014-FINAL.pdf.

2.2.3 Snow depth

Natural daily snow depth was available for 18 weeks in each year from 1997-2014, commencing on the first Sunday of June. Measurements, taken by resort staff each morning, are the average of snow depths in multiple plots (up to four) per resort. Snow depths in artificial snow-making areas were available for the years 2006-2014, at all resorts except Mount Stirling, which does not have snow-making facilities. The values recorded are total depths in the area, being the sum of natural and artificial snow. During times of abundant natural snowfall, natural snow depth is reported for the snowmaking areas (ARCC 2013). The daily snow depths were aggregated to weekly time series as maximum values for the 7 day periods.

2.2.4 Statistical Analyses

Weekly visitation data (visitor number and visitor-days) was compared to weekly snow depth time series from available daily data in sites with and without snowmaking over the winter season for the six resorts during the eighteen years 1997 to 2014. The snow depth time series were represented as anomalies from seasonal means within years and resorts to minimize spurious correlations between slope and intercept estimates of visitation response.

1. Linear mixed effects regressions to compare across years and resorts (LaP analysis)

The Landscape and Policy analysis used linear mixed effects regressions of the relationship between snow depth and visitor numbers and duration of stay. Separate models were run for natural and artificial snow depth, due to their strong collinearity. Snow depth was included as a fixed effect, while resort and year were included as random effects to highlight general relationships between visitation and snow depth at any potential resort location and in years other than those for which observations were available. The final models were of the form:

$$y_{ijk} = x_{ijk} + \left(x_{ij} \middle| resort_i\right) + \left(x_{ij} \middle| year_j\right) + e_{ijk}$$

where y is the visitation response (visitor numbers, visitor-days), x is a fixed-effects term for the weekly, *k* =1,2,…,18, mean snow depth (natural snow, artificial snow), centred for each resort, *i* =1,2,…,6, and year, *j*=1,2,…,16. The terms in parentheses are random-effects adjustments to the slope and intercept of *x*, grouped by resort and year, respectively.

This model was chosen using likelihood ratio tests to compare improvements in fit from models including altitude, and models with and without separate intercepts and slopes per resort and year. Model assumptions were checked using visual inspection of residual plots, which did not indicate any strong deviations from homoscedasticity or normality. Analyses were done in the R statistical package (R Core Team 2014) and lme4 (Bates et al. 2014). The R script is provided in Appendix A.

To assess the impact of snow making on visitation patterns, the model was re-run using the subset of years for which snow depth data in artificial snow-making areas were available (2006-2014). The relationship between visitor numbers and snow depth outside snow-making areas were compared with that in snowmaking areas. This approach was used because visitation data were only available at the resort level, not for entry to artificial snow areas, so the visitor data could not be partitioned between natural and artificial snow areas. This analysis therefore assesses the differential response associated with snow depth in the snow-making areas and natural snow depth.

The LaP researchers cautioned against making a direct estimate of the relationship between visitation and snow depth in the artificial snow-making areas because of the limitations in the data. They recommended that data on visitation patterns to particular snow-making areas be collected, to improve the ability to assess the effect of snow-making in the future.

2.3 Results and Discussion

2.3.1 Snow depth and visitation patterns from 1997–2014

During the period 1997–2014, the resorts reported an average of approximately 6,200 visitors per week, but there was considerable variability between the six destinations. Mt Buller (13,990 visitors/week) attracted more than 40 times the number at Mt Stirling (326 visitors/week). The average number of visitor-days shows a similar pattern across the resorts. Positive growth in visitor numbers and visitor-days was recorded at all resorts between 1997 and 2014. Summary statistics of the visitation patterns and snow depth for individual resorts are presented in Table 2.2 and Figure 2.2. The high altitude resorts (Mount Buller, Falls Creek and Mount Hotham) attract more visitors per season, and visitors stay for longer in these resorts if there is additional snowfall. All resorts have experienced higher visitations in some recent years suggesting that advertising campaigns, snow-making and improvements to facilities have been successful in maintaining visitor numbers.

Table 2.2: Weekly snow depth and visitation data for the six ski resorts in Victoria, Australia

Resort	Year	Maximum daily snow depth (cm)						Visitation					
		Natural			Artificial			Visitor number			Visitor days		
		Mean	SD	Median	Mean	SD	Median	Mean	SD	Median	Mean	SD	Median
Overall	1997	32	27	25	-	-	-	5,408	6,256	2,618	10,198	11,802	4,188
	2014	53	41	58	70	56	74	7,259	8,764	3,775	13,209	14,992	8,503
	Average*	47	48	32	61	51	54	6,244	6,777	3,662	11,777	13,266	5,565
Falls Creek	1997	51	34	47	-	-	-	7,149	4,506	7,678	16,718	10,163	18,050
	2014	88	56	100	107	64	125	7,758	5,271	9,737	19,787	12,797	24,215
	Average	82	55	79	89	52	93	8,320	5,033	8,777	19,033	11,305	20,790
Lake Mountain	1997	21	22	14	-	-	-	4,943	4,760	2,961	4,883	4,818	2,961
	2014	17	18	9	44	30	43	7,306	7,496	3,504	7,306	7,496	3,504
	Average	20	20	14	28	28	20	5,438	5,050	3,840	5,317	5,060	3,732
Mt Baw Baw	1997	25	22	23	-	-	-	1,443	1,087	1,328	2,021	1,462	1,862
	2014	21	23	11	37	32	38	3,735	3,514	2,674	5,191	4,869	3,829
	Average	31	28	25	31	32	23	2,074	1,763	1,739	2,894	2,581	2,307
Mt Buller	1997	30	23	22	-	-	-	13,507	8,447	14,242	23,450	14,392	25,587
	2014	60	41	70	75	48	98	17,477	13,827	18,677	27,658	20,661	33,643
	Average	53	40	45	74	46	75	13,990	9,107	13,520	25,005	15,672	26,364
Mt Hotham	1997	44	31	35	-	-	-	5,127	3,623	5,507	13,865	9,491	14,899
	2014	76	59	94	85	67	94	6,868	4,686	7,945	18,765	13,024	20,194
	Average	85	57	81	84	55	87	7,037	4,469	7,228	18,027	11,579	19,174
Mt Stirling	1997	25	20	8	-	-	-	279	493	0	251	438	0
	2014	54	41	58	-	-	-	408	443	218	546	548	395
	Average	31	28	23	-	-	-	326	368	165	388	454	198

*Averages are for the period 1997 – 2014 for natural snow depth and 2006-2014 for artificial snow depth.

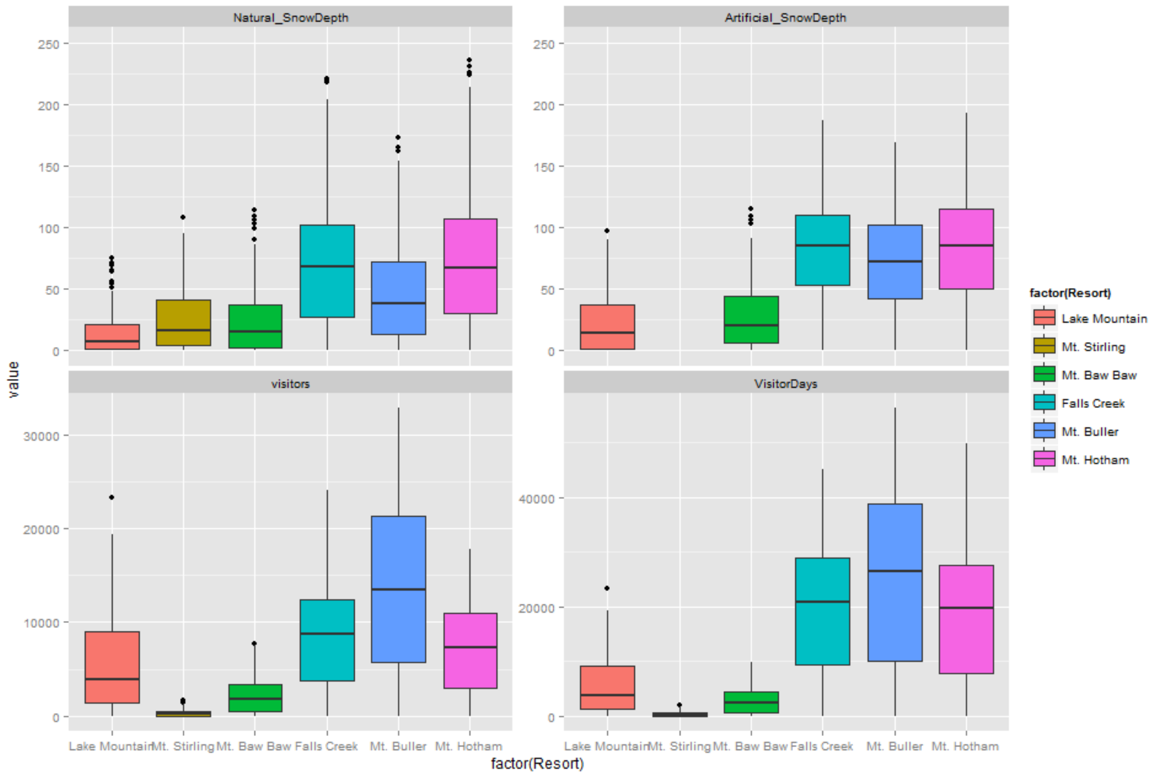

Figure 2.2: Natural snow depth, artificial snow depth, visitor numbers and visitor days at the six Victorian resorts between 1997 and 2014. The boxes represent the 90th percentile, the line is the median value, and dots indicate outliers.

2.3.2 Relationship between natural snow depth and visitation across all resorts and years (LaP analyses)

There is a significant positive relationship between maximum snow depth and visitation patterns. The average number of visitors associated with the average maximum weekly natural snow depth across all resorts and all years was 6,188 (Table 2.3). The corresponding average duration of stay, calculated by dividing the number of visitor days by the number of visitors, was 2 days. For every 1cm more natural snow, there was an increase of 110 visitors (1.8% increase), and 187 more visitor-days (1.6% increase) across all resorts.

Most of the variability in visitor number is associated with the resorts themselves, and this accounts for 4.8 times the variability associated with yearly fluctuations (SD for Resort / SD for Year). Variability in the rates at which visitor numbers change with incremental snow depth is slightly greater for resorts than for years, with variability across resorts accounting for 1.4 times the variability associated with yearly fluctuations. The ratio of the intercepts in visitor days between resorts and years (6.5 times) is slightly higher than the estimate for visitor number, and variability in the incremental change rates for visitor-days (slope) associated with years is similar (105) to that for resorts (102). This suggests that duration of stay is influenced less strongly by annual variation in snow depth than the number of visitors is. One interpretation of this is that once the decision to book a skiing holiday is made, perhaps influenced by prevailing snow conditions, the decision to alter the length of stay is less elastic.

Understanding Regression Models

Regression analysis is a tool for describing a relationship between variables, but cannot be used to infer cause and effect. While there may be a statistical relationship between snow depth and visitor numbers, for example, we cannot say that the change in snow depth caused visitor numbers to change. There may be many other factors, not considered, that visitor numbers were responding to (such as economic conditions). Additionally, making inferences about the relationship outside the range of the observations can be problematic. For example, visitor numbers could plateau, or decline, at very high snow depths because of difficult road access.

The intercept (or constant) term in a linear regression analysis is the value at which the fitted line crosses the y-axis. Here, because we used the values of snow depth calculated as anomalies from seasonal means within years and resorts, the intercept can be interpreted as the mean of the response variable (eg. visitor number) at the mean value of the predictor variable (snow depth). The slope of the fitted line is often of more interest than the intercept, because it describes the rate at which the response variable changes with an incremental change in the predictor variable.

In Table 2.3, the intercept value for visitor number is 6,188, which means that at the average snow depth, there were 6,188 visitors across all resorts and all years. The slope is 110 ± 31.5, which can be interpreted as being an increase of 110 more visitors, give or take 31.5, for every additional 1cm of snow.

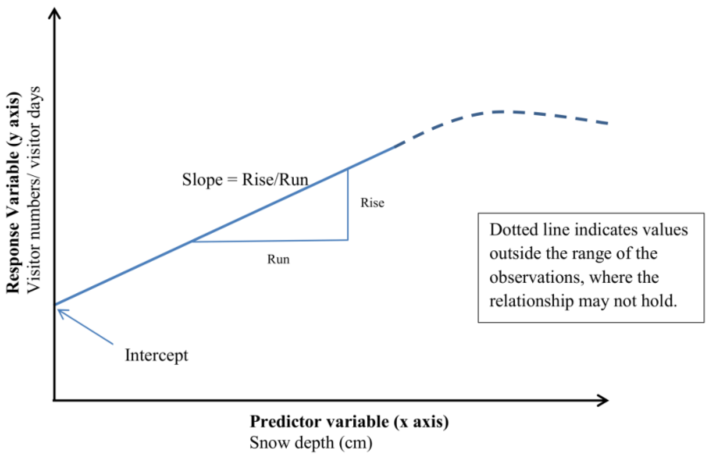

Table 2.3: Linear mixed effect model summary: Relationship between maximum natural snow depth and visitation (visitor number and visitor days)

Model features			Visitor number	Visitor days
Fixed effect				
	Intercept	Estimate	6,188	11,777.30
		Std. Error	1,985.81	4,167.94
		t-value	3.116	2.826
	Slope (Snow)	Estimate	110	186.99
		Std. Error	31.52	48.78
		t-value	3.490	3.834
		Correlation	0.60	0.70
Random effects				
Year	Intercept	Std. Dev.	1,007.20	1,577.30
	Slope (Snow)	Std. Dev.	51.80	105
		Correlation	-0.61	-0.63
Resort	Intercept	Std. Dev.	4,824.84	10,161.7
	Slope (Snow)	Std. Dev.	70.56	101.6
		Correlation	0.69	0.86
Residual		Std. Dev.	3,720.83	6,768.8

Model coefficients for visitor number and visitor days by maximum weekly snow depth are presented in Table 3.4. These values result from the addition of per resort and yearly random effects adjustments to the fixed effects values presented in Table 2.3. The resort intercept column shows the expected number of visitors at the seasonal mean maximum weekly snow depth per resort, averaged across all years. Conversely, the intercept column for the year group shows the expected annual visitor number associated with the average maximum weekly snow depth across all resorts. Similarly, the slope column (snow depth) shows the rate of change in visitor numbers and visitor days for every centimetre change in snow depth.

In general, visitation was most responsive to snow depth (natural snow and snow-making) at the higher altitude resorts. Mount Buller, in particular, with 191 visitors per cm of snow and 338 visitor days per cm of snow, gains the most from increases in snow depth. Mount Stirling was the least responsive to changes in snow depth (28 visitors per cm; 55 visitor days per cm). The exception to this was the Lake Mountain resort, which showed high values for the slope terms for both visitors and visitor days (200 per cm and 215 per cm respectively). This sensitivity at Lake Mountain is likely to be due to the close proximity of the city of Melbourne. That Lake Mountain is comparable to Mount Buller in this regard indicates the strength of the proximity appeal, although the demographic profile and motivations are likely to differ between groups visiting these locations.

The LaP analysis also revealed interesting information about the inter-annual variation in visitor numbers. The variability associated with yearly variations was found to be smaller than the resort effects. The year 2006 was a particularly bad year for visitor numbers, but also showed the highest rate of change with snow depth (slope). A plausible explanation is that although visitor numbers were low in response to a poor snow season, demand remained high and appeared responsive to incremental changes in snow conditions. Visitor responsiveness also varied substantially across resorts in 2006.

Three of the last five seasons (2010, 2012, 2014) are in the top five strongest years in terms of visitor number and visitor days at the mean snow depth (highest intercept values). There was an average of 7,173 visitors across all resorts in 2010; 7,315 visitors in 2012; and 7,046 visitors in 2014, compared to the mean of 6,188 across all years. Taken alone, these results suggest that demand remains strong, and suggests that visitation is not yet experiencing a negative impact from current levels of climate warming. On the other hand, four of those top five years are also associated with below average slope values. Compared to the mean of 110 more visitors for every additional 1cm of snow, the rate of change in these four years ranged from 42 more visitors in 2012 to 74 more visitors per cm snow in 2004. This could indicate a slow-down in the rate of response, even while numbers currently remain high.

Table 2.4: Coefficient values from linear mixed effect models for maximum natural snow depth with visitor number and visitor-days, respectively

	Visitor number		**Visitor days**	
	Intercept	**Slope (snow depth)**	**Intercept**	**Slope (snow depth)**
Year				
1997	5,508	126	10,519	200
1998	5,473	139	10,139	245
1999	5,031	140	9,834	238
2000	7,227	46	13,386	60
2001	4,620	90	9,646	133
2002	6,020	139	11,050	247
2003	6,750	34	12,845	33
2004	7,659	74	13,668	109
2005	6,305	158	11,695	269
2006	4,429	225	9,121	445
2007	6,818	130	12,594	233
2008	6,419	82	12,467	131
2009	6,204	131	12,383	247
2010	7,173	43	13,391	50
2011	5,776	149	11,333	269
2012	7,315	42	13,652	76
2013	5,612	107	11,401	181
2014	7,046	126	12,867	199
Resort				
Falls Creek	8,282	95	19,077	214
Lake Mountain	5,413	200	5,364	215
Mt Baw Baw	2,157	63	2,898	94
Mt Buller	13,938	191	25,004	338
Mt Hotham	7,001	84	18,003	206
Mt Stirling	338	28	388	55

2.3.3 Impact of snow-making

The relationship between visitor number and snow depth in and outside snow-making areas is very similar (Table 2.5). Across all resorts and years, the intercept values are essentially identical, reflecting similar visitor numbers at average natural and artificial snow depths. While the mean rate of change to visitor numbers is slightly higher in response to natural snow depth compared to artificial snow depth, this is not statistically significant (shown by the standard errors associated with the slope terms).

However, when resorts and years are considered separately, the rate of change in visitor numbers is consistently greater for natural snow areas compared to snow-making areas. Visitors at the Mount Buller resort were the most responsive to changes in snow depth, compared to the other resorts (Table 2.6) (natural snow areas slope of 228; artificial areas slope of 164). Mount Baw Baw had the least responsive visitors (natural snow areas slope of 72; artificial areas slope of 57). Falls Creek and Mount Hotham had similar visitor responses for both natural and artificial snow depth. Visitors to Lake Mountain respond strongly to changes in natural snow depth, but the rate of change in artificial snow depth is also relatively high (natural snow areas slope of 211; artificial areas slope of 138). The higher sensitivity of visitor numbers to natural snow making suggests that visitor's decisions are still strongly influenced by natural snow, a perception that could be changed with greater awareness of the effectiveness of snow-making.

An important difference between the natural and artificial snow models is the reduction in variability associated with artificial snow depth (shown by the standard errors in Table 2.5). Overall, visitor number is 33% less volatile in response to changes in snow depth in the snow-making areas. Snow-making is therefore effective at improving the reliability of the seasons for skiing. This is important to ensure a minimum number of visitors every year and provide a degree of certainty for visitors planning holidays in advance.

Table 2.5: Linear mixed effect model summary: Relationship between visitor number with maximum snow depth outside snow-making areas (Natural) and in snowmaking areas (Artificial). This analysis differs from the full mixed model, as it was applied only to those years for which snow depth in snow-making areas was available (2006-2014). No snow-making occurs at Mt Stirling.

Model features			Natural	Artificial
Fixed effect				
	Intercept	Estimate	7,562.75	7,562.54
		Std. Error	2,051.85	2,050.42
		t-value	3.686	3.688
	Slope (Snow)	Estimate	139.13	102.02
		Std. Error	40.75	26.19
		t-value	3.414	3.896
		Correlation	0.41	0.48
Random effects				
Year	Intercept	Std. Dev.	1,114.00	1,108.41
	Slope (Snow)	Std. Dev.	65.49	44.00
		Correlation	-0.83	-0.72
Resort	Intercept	Std. Dev.	4,500.18	4,496.93
	Slope (Snow)	Std. Dev.	75.45	47.14
		Correlation	0.60	0.70
Residual		Std. Dev.	4,158.01	4,282.61

Table 2.6: Coefficient values from linear mixed effect models: Relationship between visitor number with maximum snow depth outside snow-making areas (Natural) and in snowmaking areas (Artificial)

	Natural		Artificial	
	Intercept	**Slope (snow depth)**	**Intercept**	**Slope (snow depth)**
Year				
2006	5,389	268	5,509	167
2007	8,033	151	8,039	127
2008	7,772	101	7,722	75
2009	7,415	156	7,511	97
2010	8,609	58	8,530	53
2011	6,956	173	6,869	144
2012	8,773	61	8,800	37
2013	6,892	134	6,790	102
2014	8,226	150	8,293	116
Resort				
Falls Creek	7,938	94	7,945	77
Lake Mountain	5,487	211	5,487	138
Mt Baw Baw	2,488	72	2,491	57
Mt Buller	14,653	228	14,645	164
Mt Hotham	7,248	90	7,244	74
Mt Stirling	-	-	-	-

2.3.4 Simple linear regressions of snow depth and visitation at individual resorts

To illustrate the results of the LaP analysis, simple linear regressions of snow depth against visitation for the period 1997-2014 are presented for each resort separately.

The relationship between snow depth and visitor numbers and visitor days is significant and positive at all resorts (Tables 2.7 & 2.8; Figures 2.3 & 2.4). The slope of the regression line, indicating the strength of the relationship, varies across different resorts, as shown in the previous analysis. Lake Mountain and Mt Buller have the greatest increase in visitors and visitor days with increased snow. The similarity in the relationship between visitor number and snow depth in and outside snowmaking areas is shown by the close intercepts and slopes of the lines for each resort. Enlarged figures showing the relationship between snow depth and visitor numbers and the regression equation at each resort can be found in Appendix B, Part I.

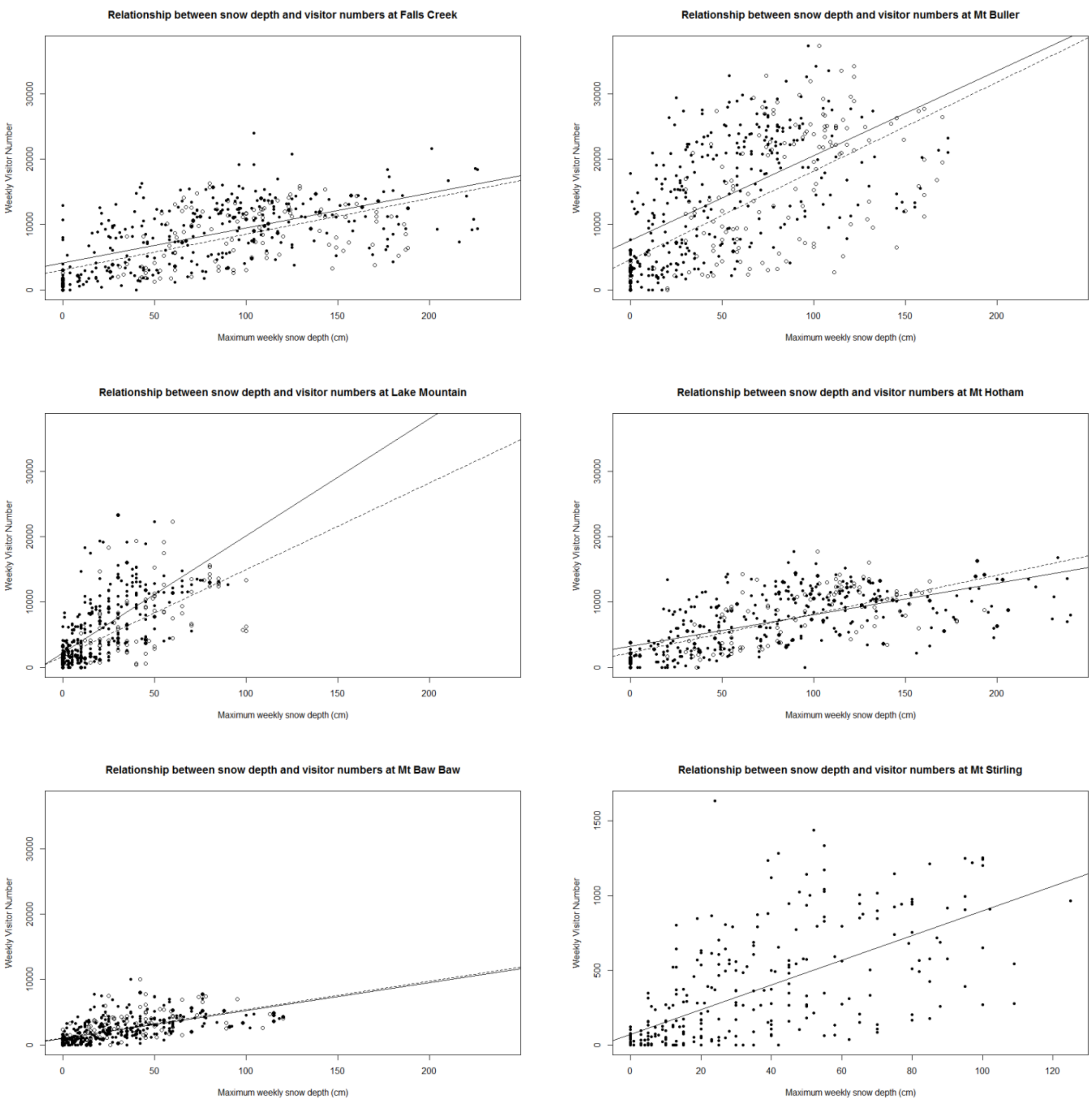

Figure 2.3: Relationship between maximum snow depth (cm) and weekly visitor numbers from 1997-2014 at the six Victorian alpine resorts. Closed circles represent natural snow depth, open circles represent snow depth in snow-making areas (natural + artificial snow). Lines are linear regressions for natural (solid lines) and artificial snow areas (dashed lines). Note different scale on Mt Stirling plot. Enlarged figures are also presented in Appendix B, Part I.

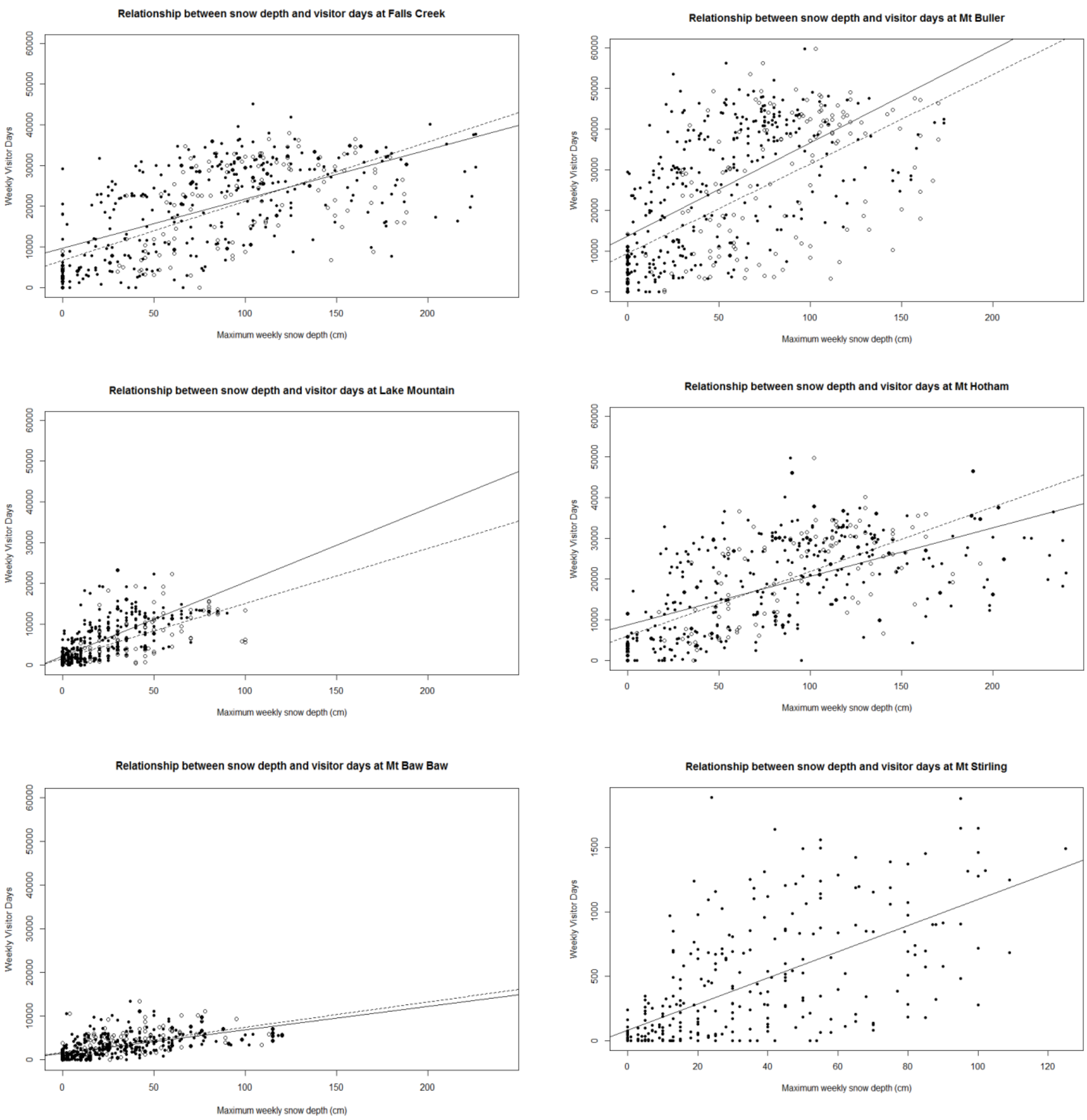

Figure 2.4: Relationship between maximum snow depth (cm) and weekly visitor days from 1997-2014 at the Victorian alpine resorts. Closed circles represent natural snow depth, open circles represent snow depth in snow-making areas (natural + artificial snow). Lines are linear regressions for natural (solid lines) and artificial snow areas (dashed lines). Note different scale on Mt Stirling plot. Enlarged figures are also presented in Appendix B, Part I.

2.4 Conclusions

Visitors to the Victorian alpine resorts are responsive to changes in snow conditions. On average, the number of visitors increases with maximum snow depth, both natural and artificial, and they stay for longer. Visitor response differs at different resorts, with the higher altitude resorts showing the greatest increases in visitor numbers and duration of stay with increased snow depth (both natural and artificial). Visitors to Lake Mountain were also very responsive because of its proximity to Melbourne. Snow-making did not substantially alter the relationship between snow cover and visitation, but it did reduce the inter-annual variability in visitor numbers by a third. Visitors were more responsive to changes in natural snow depth than to changes in artificial snow depth. This suggests there may be opportunities to increase potential visitors' understanding of the extent of current snow-making and its success in maintaining reliable skiing conditions.

Table 2.7: Regression results for resorts - visitor numbers vs maximum weekly snow depth (cm)

	Natural snow				Artificial snow				
	F_{df}	r^2	Intercept	Slope	F_{df}	r^2	Intercept	Slope	
Falls Creek	$181.2_{1,319}$	0.36	4164.6 ± 381.8	53.3 ± 4.0	$94.15_{1,158}$	0.37	3071.8± 83.1	54.8 ± 5.6	***
Lake Mountain	$307.8_{1,315}$	0.49	2179.8 ± 274.4	179.5 ± 10.2	$134.8_{1,153}$	0.47	1667.6 ± 460.4	132.6 ± 11.4	***
Mt Baw Baw	$185.1_{1,316}$	0.37	1011.5 ± 120.4	42.5 ± 3.1	$103.3_{1,156}$	0.40	1109.0 ± 191.0	43.1 ± 4.2	***
Mt Buller	$152.7_{1,321}$	0.32	7576.6 ± 666.1	129.6 ± 10.5	$102.4_{1,321}$	0.39	4609.3 ± 172.3	135.9 ± 13.4	***
Mt Hotham	$204.2_{1,320}$	0.39	3254.0 ± 328.7	48.1 ± 3.4	$153.9_{1,158}$	0.49	2287.3 ± 479.9	59.1 ± 4.8	***
Mt Stirling	$232.2_{1,314}$	0.42	72.0 ± 22.9	8.3 ± 0.5	-	-	-	-	

***sig at 0.001 level

Table 2.8: Regression results for resorts - visitor days vs maximum weekly snow depth (cm)

	Natural snow				Artificial sno9.0				
	F_{df}	r^2	Intercept	Slope	F_{df}	r^2	Intercept	Slope	
Falls Creek	$188.5_{1,322}$	0.37	9652.1 ± 846.4	121.0 ±8.8	$127.6_{1,160}$	0.44	6633.0 ± 1326.0	145.7 ± 12.9	***
Lake Mountain	$324.1_{1,322}$	0.50	2083.8 ± 267.9	181.8 ±10.1	$152.3_{1,160}$	0.48	1523.0 ± 431.8	135.2 ± 11.0	***
Mt Baw Baw	$152.4_{1,322}$	0.32	1456.9 ± 166.0	53.6 ± 4.3	$93.94_{1,160}$	0.37	1609.7 ± 264.4	57.7 ± 5.9	***
Mt Buller	$166.6_{1,322}$	0.34	13702.1± 1126.0	229.2 ± 17.8	$88.83_{1,160}$	0.35	9424.2 ± 2030.6	220.0 ± 23.34	***
Mt Hotham	$179.4_{1,322}$	0.36	8715.4 ± 866.0	119.2 ± 8.9	$155.5_{1,160}$	0.49	5952.6 ± 1272.0	158.5 ± 12.71	***
Mt Stirling	$235.2_{1,322}$	0.42	78.5 ± 28.0	10.2 ± 0.7	-	-	-	-	

***sig at 0.001 level

2.5 References

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Appendix A, Part I

```
###R script to run the analysis of visitation patterns and snow depth at the Victorian Alpine Resorts

##install required packages

        install.packages("lme4")
        install.packages("compiler")
        install.packages("parallel")
        install.packages("boot")
##set working directory - change pathway to directory the files are saved in
        setwd('C:/your path/')
##read the data from csv file
  resort_data<-read.csv('C:/your path /resort_data_final_to_ARCC.csv', header=T)
  head(resort_data)

##make resort and year factors
  resort_data<- within(resort_data, {
    Year <- factor(resort_data$Year)
    Resort <- factor(resort_data$Resort)
    })

##Analysis done on anomalies, to minimise spurious correlations between slopes and intercept
estimates of ##visitation response
##calculate anomalies when updating data to include recent years
## take mean by year and resort, ignoring NA
  means = aggregate(list(Mean.Snow = resort_data$Natural_SnowDepth),
        by = list(Year = resort_data$Year, Resort = resort_data$Resort),
        FUN = function(x) mean(x, na.rm=TRUE))
  resort_data$Nat_Anomaly = NA # initialise new column called "Nat_Anomaly"

## calculate each value of new column by taking away the relevant mean
  for (i in 1:nrow(resort_data))
    resort_data$Nat_Anomaly[i] = resort_data$Natural_SnowDepth[i] -
means$Mean.Snow[means$Year
        == resort_data$Year[i] & means$Resort == resort_data$Resort[i]]
  ##save as new csv file

  write.csv(resort_data, "filename.csv", row.names = FALSE)
```

```
################################################################################
##Check assumptions of linearity, equal variances, using residual plot, histogram of residuals and Q-Q plot
  install.packages("ggplot2")
  ggpairs(resort_data[, c("Resort", "Nat_Anomaly", "Art_Anomaly", "visitors", "VisitorDays")])
## Fit a simple linear regression model between visitors and natural and artificial snow depth separately, ##because highly collinear
##natural snow
  fit_nat<-lm(visitors ~ Nat_Anomaly,data=resort_data)
  plot(fitted(fit_nat),residuals(fit_nat))
  hist(residuals(fit_nat)) ##normality of residuals a problem if there is strong deviation from normal distribution
  qqnorm(residuals(fit_nat)) ##normal distribution will be a straight line, but some deviation is ok.

##artificial snow
  fit_art<-lm(visitors ~ Art_Anomaly,data=resort_data)
  plot(fitted(fit_art),residuals(fit_art))
  hist(residuals(fit_art))
  qqnorm(residuals(fit_art))

##do the same for visitor days
##natural snow
  fit_nat_days<-lm(VisitorDays ~ Nat_Anomaly,data=resort_data)
  plot(fitted(fit_nat_days),residuals(fit_nat_days))
  hist(residuals(fit_nat_days))
  qqnorm(residuals(fit_nat_days))

##artificial snow
  fit_art_days<-lm(VisitorDays ~ Art_Anomaly,data=resort_data)
  plot(fitted(fit_art_days),residuals(fit_art_days))
  hist(residuals(fit_art_days))
  qqnorm(residuals(fit_art_days))

################################################################################
##Mixed effects logistic regression - to include fixed and random effects. Visitor numbers and visitor days ##analysed separately
##visitors first:
```

```
##natural snow
  visitor_natural_snow_model <- lmer(visitors ~ Nat_Anomaly +
        (1 + Nat_Anomaly | Resort) + (1 + Nat_Anomaly | Year), data = resort_data, REML=TRUE)
  summary(visitor_natural_snow_model) ##to get all estimates, std error, sds, correlations
  coefficients(visitor_natural_snow_model)##to get coefficients for years and resorts

  visitordays_natural_snow_model <- lmer(VisitorDays ~ Nat_Anomaly +
        (1 + Nat_Anomaly | Resort) + (1 + Nat_Anomaly | Year), data = resort_data, REML=TRUE)

  summary(visitordays_natural_snow_model)
  coefficients(visitordays_natural_snow_model)

##artifical snow
  visitor_artificial_snow_model <- lmer(visitors ~ Art_Anomaly +
        (1 + Art_Anomaly | Resort) + (1 + Art_Anomaly | Year), data = resort_data, REML=TRUE)
  summary(visitor_artificial_snow_model)
  coefficients(visitor_artificial_snow_model)

 visitordays_artificial_snow_model <- lmer(VisitorDays ~ Art_Anomaly +
          (1 + Art_Anomaly | Resort) + (1 + Art_Anomaly | Year), data = resort_data, REML=TRUE)
  summary(visitordays_artificial_snow_model)
  coefficients(visitordays_artificial_snow_model)

##########################To do regressions on resorts separately and plot
##save each resort as a separate object
  falls <- subset(resort_data, Resort=="Falls Creek")
  lakem <- subset(resort_data, Resort=="Lake Mountain")
  bawbaw <- subset(resort_data, Resort=="Mt. Baw Baw")
  buller <- subset(resort_data, Resort=="Mt. Buller")
  hotham <- subset(resort_data, Resort=="Mt. Hotham")
  stirling <- subset(resort_data, Resort=="Mt. Stirling")

##run regression analyses
##natural snow depth vs visitor number
  falls_reg <- lm(visitors~Natural_SnowDepth,data=falls); summary(falls_reg)
  lakem_reg <- lm(visitors~Natural_SnowDepth,data=lakem); summary(lakem_reg)
```

```
  bawbaw_reg <- lm(visitors~Natural_SnowDepth,data=bawbaw); summary(bawbaw_reg)
  buller_reg <- lm(visitors~Natural_SnowDepth,data=buller); summary(buller_reg)
  hotham_reg <- lm(visitors~Natural_SnowDepth,data=hotham); summary(hotham_reg)
  stirling_reg <- lm(visitors~Natural_SnowDepth,data=stirling); summary(stirling_reg)

##artificial snow depth - none for Stirling
  falls_reg_art <- lm(visitors~Artificial_SnowDepth,data=falls); summary(falls_reg_art)
  lakem_reg_art <- lm(visitors~Artificial_SnowDepth,data=lakem); summary(lakem_reg_art)
  bawbaw_reg_art <- lm(visitors~Artificial_SnowDepth,data=bawbaw); summary(bawbaw_reg_art)
  buller_reg_art <- lm(visitors~Artificial_SnowDepth,data=buller); summary(buller_reg_art)
  hotham_reg_art <- lm(visitors~Artificial_SnowDepth,data=hotham); summary(hotham_reg_art)
##plot regressions of snow depth vs visitor number (natural and artificial on same plot)
##Falls Creek
  plot(visitors~Natural_SnowDepth, data=resort_data, type='n', ylab="Weekly Visitor Number",
        xlab="Maximum weekly snow depth (cm)",
        main='Relationship between snow depth and visitor numbers at Falls Creek')
  points(falls$Natural_SnowDepth,falls$visitors, pch=20)
  points(falls$Artificial_SnowDepth,falls$visitors, pch=1)
  abline(falls_reg, lty=1)
  abline(falls_reg_art, lty=2)

##Lake Mountain
  plot(visitors~Natural_SnowDepth, data=resort_data, type='n', ylab="Weekly Visitor Number",
        xlab="Maximum weekly snow depth (cm)",
        main='Relationship between snow depth and visitor numbers at Lake Mountain')
  points(lakem$Natural_SnowDepth,lakem$visitors, pch=20)
  points(lakem$Artificial_SnowDepth,lakem$visitors, pch=1)
  abline(lakem_reg, lty=1)
  abline(lakem_reg_art, lty=2)

##Mt Baw Baw
  plot(visitors~Natural_SnowDepth, data=resort_data, type='n', ylab="Weekly Visitor Number",
        xlab="Maximum weekly snow depth (cm)",
        main='Relationship between snow depth and visitor numbers at Mt Baw Baw')
  points(bawbaw$Natural_SnowDepth,bawbaw$visitors, pch=20)
  points(bawbaw$Artificial_SnowDepth,bawbaw$visitors, pch=1)
```

```
  abline(bawbaw_reg, lty=1)
  abline(bawbaw_reg_art, lty=2)

##Mt Buller
  plot(visitors~Natural_SnowDepth, data=resort_data, type='n', ylab="Weekly Visitor Number",
       xlab="Maximum weekly snow depth (cm)",
       main='Relationship between snow depth and visitor numbers at Mt Buller')
  points(buller$Natural_SnowDepth,buller$visitors, pch=20)
  points(buller$Artificial_SnowDepth,buller$visitors, pch=1)
  abline(buller_reg, lty=1)
  abline(buller_reg_art, lty=2)

##Mt Hotham
  plot(visitors~Natural_SnowDepth, data=resort_data, type='n', ylab="Weekly Visitor Number",
       xlab="Maximum weekly snow depth (cm)",
       main='Relationship between snow depth and visitor numbers at Mt Hotham')
  points(hotham$Natural_SnowDepth,hotham$visitors, pch=20)
  points(hotham$Artificial_SnowDepth,hotham$visitors, pch=1)
  abline(hotham_reg, lty=1)
  abline(hotham_reg_art, lty=2)

##Mt Stirling different scale
  plot(visitors~Natural_SnowDepth, data=stirling, type='n', ylab="Weekly Visitor Number",
       xlab="Maximum weekly snow depth (cm)",
       main='Relationship between snow depth and visitor numbers at Mt Stirling')
  points(stirling$Natural_SnowDepth,stirling$visitors, pch=20)
  abline(stirling_reg, lty=1)
##legend("bottomright", c("Natural","Artificial"), lty=c(1,2), pch=c(20,1) )

##Now for visitor days
##natural snow depth vs visitor days
  falls_reg_visitordays <- lm(VisitorDays~Natural_SnowDepth,data=falls);
summary(falls_reg_visitordays)
  lakem_reg_visitordays <- lm(VisitorDays~Natural_SnowDepth,data=lakem);
summary(lakem_reg_visitordays)
  bawbaw_reg_visitordays <- lm(VisitorDays~Natural_SnowDepth,data=bawbaw);
summary(bawbaw_reg_visitordays)
```

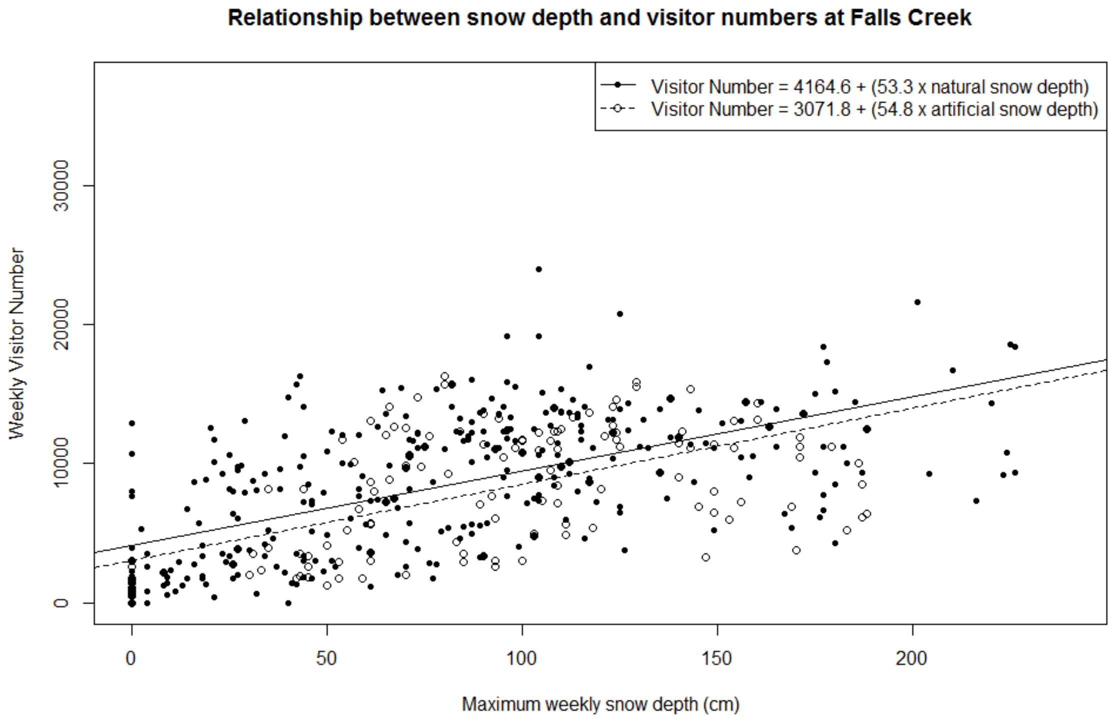
```
buller_reg_visitordays <- lm(VisitorDays~Natural_SnowDepth,data=buller);
summary(buller_reg_visitordays)

hotham_reg_visitordays <- lm(VisitorDays~Natural_SnowDepth,data=hotham);
summary(hotham_reg_visitordays)

stirling_reg_visitordays <- lm(VisitorDays~Natural_SnowDepth,data=stirling);
summary(stirling_reg_visitordays)


##artificial snow depth vs visitor days- none for Stirling

falls_reg_art_visitordays <- lm(VisitorDays~Artificial_SnowDepth,data=falls);
summary(falls_reg_art_visitordays)

lakem_reg_art_visitordays <- lm(VisitorDays~Artificial_SnowDepth,data=lakem);
summary(lakem_reg_art_visitordays)

bawbaw_reg_art_visitordays <- lm(VisitorDays~Artificial_SnowDepth,data=bawbaw);
summary(bawbaw_reg_art_visitordays)

buller_reg_art_visitordays <- lm(VisitorDays~Artificial_SnowDepth,data=buller);
summary(buller_reg_art_visitordays)

hotham_reg_art_visitordays <- lm(VisitorDays~Artificial_SnowDepth,data=hotham);
summary(hotham_reg_art_visitordays)


##plot as for visitor number

##Falls Creek

plot(VisitorDays~Natural_SnowDepth, data=resort_data, type='n', ylab="Weekly Visitor Days",
      xlab="Maximum weekly snow depth (cm)",
      main='Relationship between snow depth and visitor days at Falls Creek')
points(falls$Natural_SnowDepth,falls$VisitorDays, pch=20)
points(falls$Artificial_SnowDepth,falls$VisitorDays, pch=1)
abline(falls_reg_visitordays, lty=1)
abline(falls_reg_art_visitordays, lty=2)


##Lake Mountain

plot(VisitorDays~Natural_SnowDepth, data=resort_data, type='n', ylab="Weekly Visitor Days",
      xlab="Maximum weekly snow depth (cm)",
      main='Relationship between snow depth and visitor days at Lake Mountain')
points(lakem$Natural_SnowDepth,lakem$VisitorDays, pch=20)
points(lakem$Artificial_SnowDepth,lakem$VisitorDays, pch=1)
abline(lakem_reg_visitordays, lty=1)
abline(lakem_reg_art_visitordays, lty=2)
```

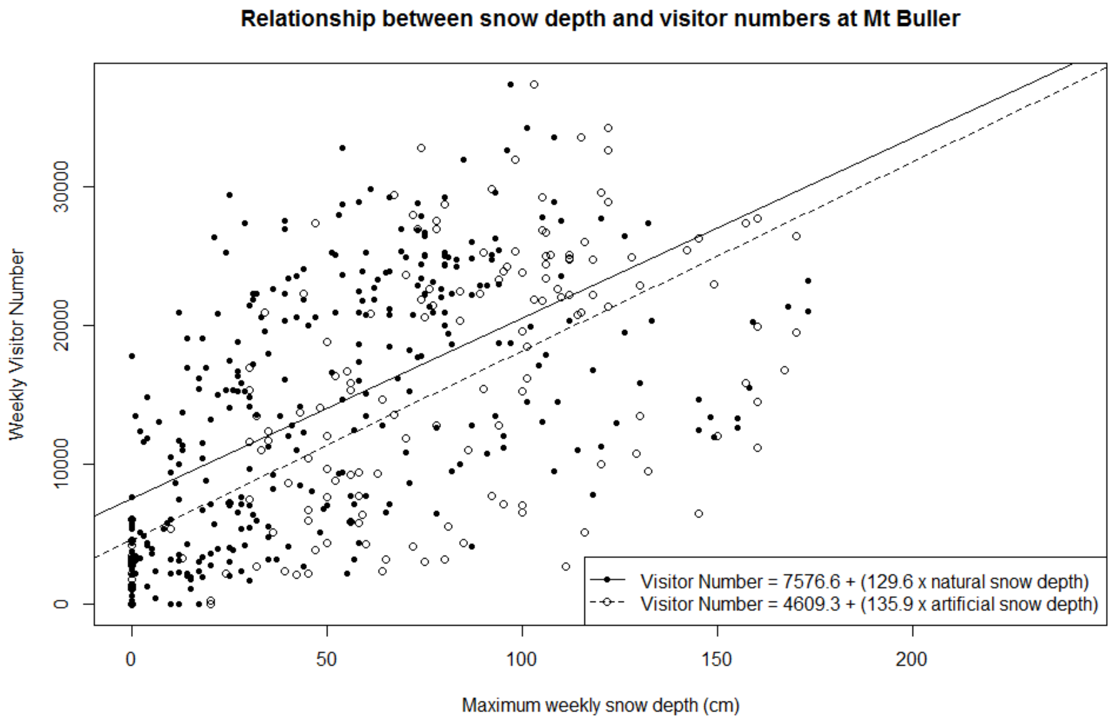
```
##Mt Baw Baw
  plot(VisitorDays~Natural_SnowDepth, data=resort_data, type='n', ylab="Weekly Visitor Days",
        xlab="Maximum weekly snow depth (cm)",
       main='Relationship between snow depth and visitor days at Mt Baw Baw')
  points(bawbaw$Natural_SnowDepth,bawbaw$VisitorDays, pch=20)
  points(bawbaw$Artificial_SnowDepth,bawbaw$VisitorDays, pch=1)
  abline( bawbaw_reg_visitordays, lty=1)
  abline(bawbaw_reg_art_visitordays, lty=2)

##Mt Buller
  plot(VisitorDays~Natural_SnowDepth, data=resort_data, type='n', ylab="Weekly Visitor Days",
       xlab="Maximum weekly snow depth (cm)",
       main='Relationship between snow depth and visitor days at Mt Buller')
  points(buller$Natural_SnowDepth,buller$VisitorDays, pch=20)
  points(buller$Artificial_SnowDepth,buller$VisitorDays, pch=1)
  abline(buller_reg_visitordays, lty=1)
  abline(buller_reg_art_visitordays, lty=2)

##Mt Hotham
  plot(VisitorDays~Natural_SnowDepth, data=resort_data, type='n', ylab="Weekly Visitor Days",
        xlab="Maximum weekly snow depth (cm)",
       main='Relationship between snow depth and visitor days at Mt Hotham')
  points(hotham$Natural_SnowDepth,hotham$VisitorDays, pch=20)
  points(hotham$Artificial_SnowDepth,hotham$VisitorDays, pch=1)
  abline(hotham_reg_visitordays, lty=1)
  abline(hotham_reg_art_visitordays, lty=2)

##Mt Stirling different scale
  plot(VisitorDays~Natural_SnowDepth, data=stirling, type='n', ylab="Weekly Visitor Days",
       xlab="Maximum weekly snow depth (cm)",
       main='Relationship between snow depth and visitor days at Mt Stirling')
  points(stirling$Natural_SnowDepth,stirling$VisitorDays, pch=20)
  abline(stirling_reg_visitordays, lty=1)

###########################################################################
```

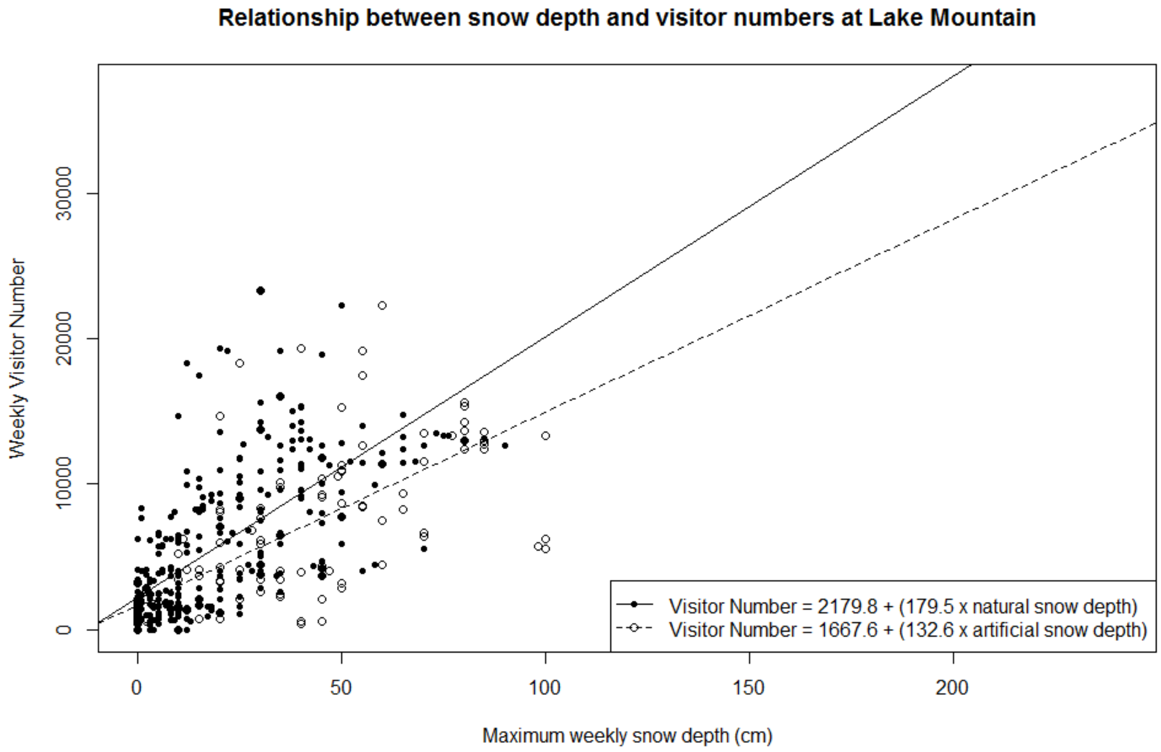
```
## re-run mixed effect model on the subset of resort_data from 2006-2014 to compare visitation
response to ##natural vs artificial snow areas within those resorts that make snow (natural should
be slightly different, ##because will only include 2006-2014)

##change pathway to directory the files are saved in

subset_data<-
read.csv('C:/Users/rmharris/Documents/Alps/alpine_resorts/resort_data_2006_2014_final_to_ARC
C.csv',
        header=T)
 head(subset_data)

 subset_data<- within(subset_data, {
  Year <- factor(subset_data$Year)
  Resort <- factor(subset_data$Resort)
 })

 visitor_natural_snow_model_subset <- lmer(visitors ~ Nat_Anomaly +
        (1 + Nat_Anomaly | Resort) + (1 + Nat_Anomaly | Year), data = subset_data, REML=TRUE)

 summary(visitor_natural_snow_model_subset) ##to get all estimates, std error, sds, correlations
 coefficients(visitor_natural_snow_model_subset) ##to get coefficients for years and resorts

 visitor_artificial_snow_model_subset <- lmer(visitors ~ Art_Anomaly +
          (1 + Art_Anomaly | Resort) + (1 + Art_Anomaly | Year), data = subset_data, REML=TRUE)

 summary(visitor_artificial_snow_model_subset) ##to get all estimates, std error, sds, correlations
 coefficients(visitor_artificial_snow_model_subset) ##to get coefficients for years and resorts
################################################################################
```

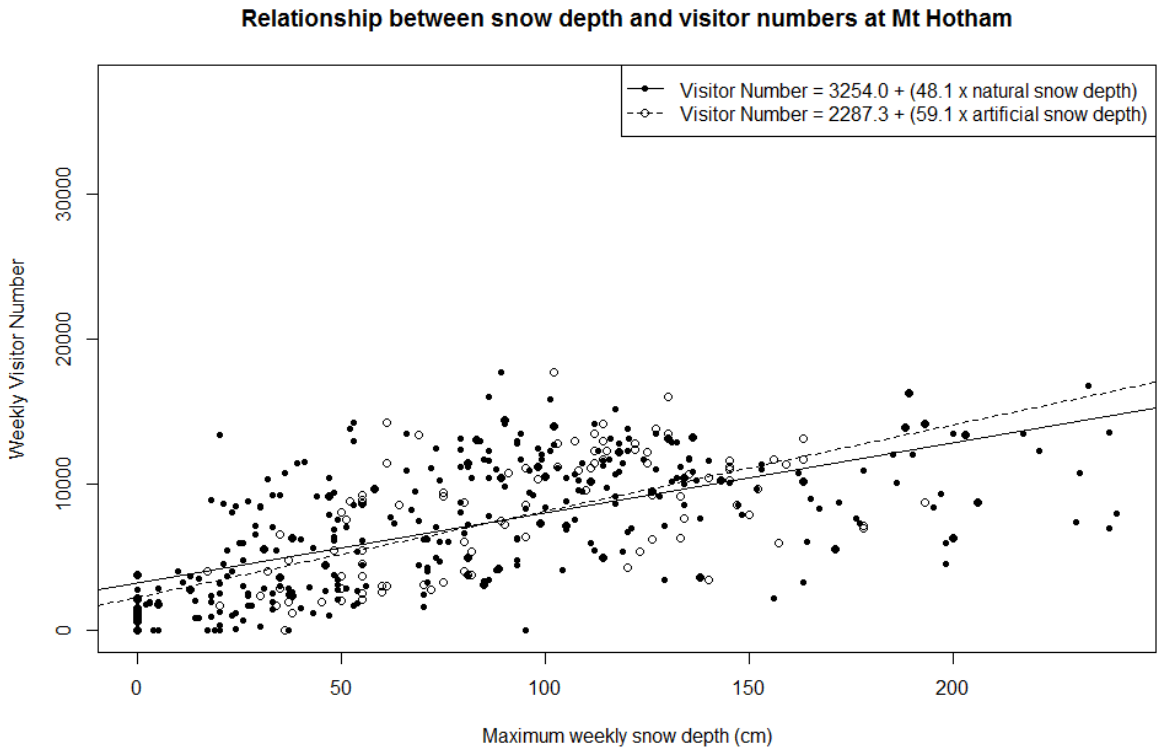
Appendix B, Part I

Enlarged figures from Figure 3.3, showing the relationship between maximum snow depth (cm) and weekly visitor numbers from 1997-2014 at the Victorian alpine resorts. Closed circles represent natural snow depth, open circles represent snow depth in snow-making areas (natural + artificial snow). Lines are linear regressions for natural (solid lines) and artificial snow areas. The standard errors associated with the regression are in Tables 3.7 & 3.8.

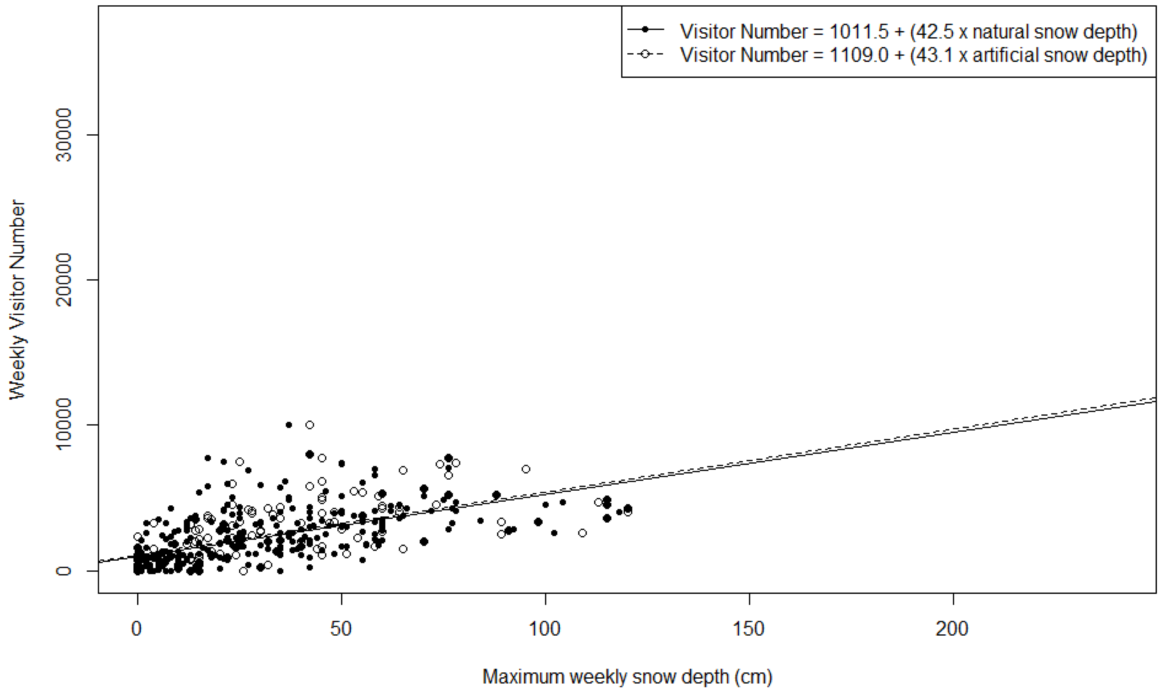




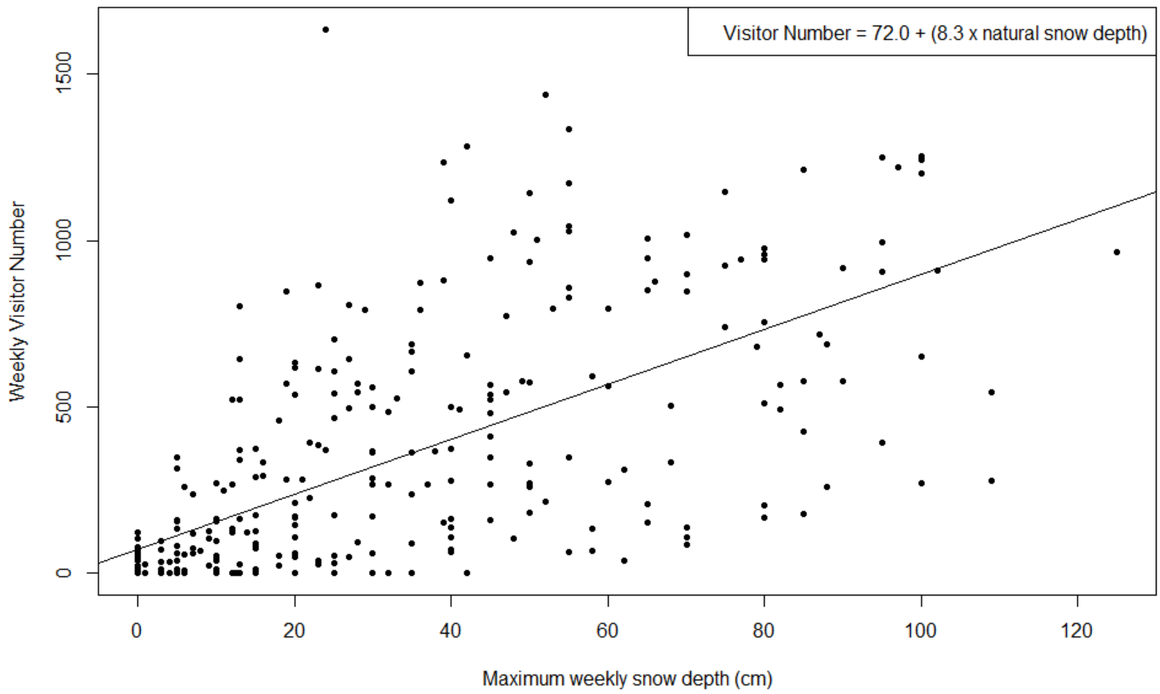

Relationship between snow depth and visitor numbers at Lake Mountain
Weekly Visitor Number
0
10000
20000
30000
0
50
100
150
200
Maximum weekly snow depth (cm)
Visitor Number = 2179.8 + (179.5 x natural snow depth)
Visitor Number = 1667.6 + (132.6 x artificial snow depth)


Relationship between snow depth and visitor numbers at Mt Hotham
Weekly Visitor Number
0
10000
20000
30000
0
50
100
150
200
Maximum weekly snow depth (cm)
Visitor Number = 3254.0 + (48.1 x natural snow depth)
Visitor Number = 2287.3 + (59.1 x artificial snow depth)

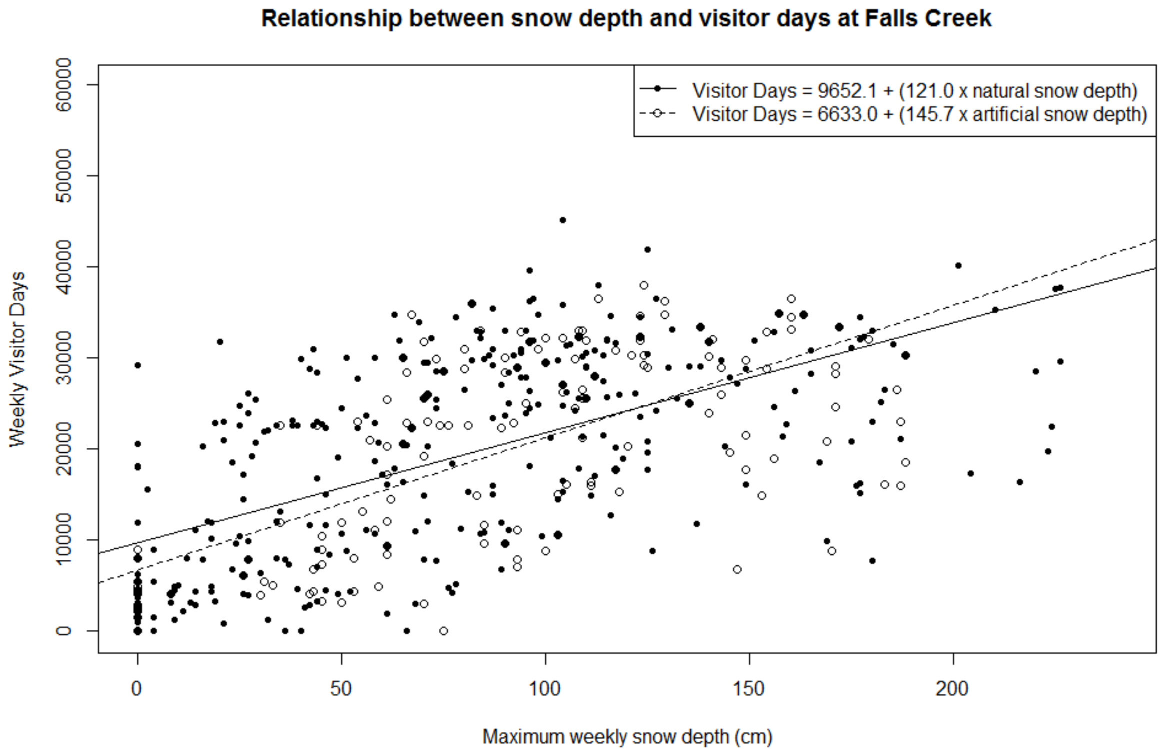
Relationship between snow depth and visitor numbers at Mt Baw Baw

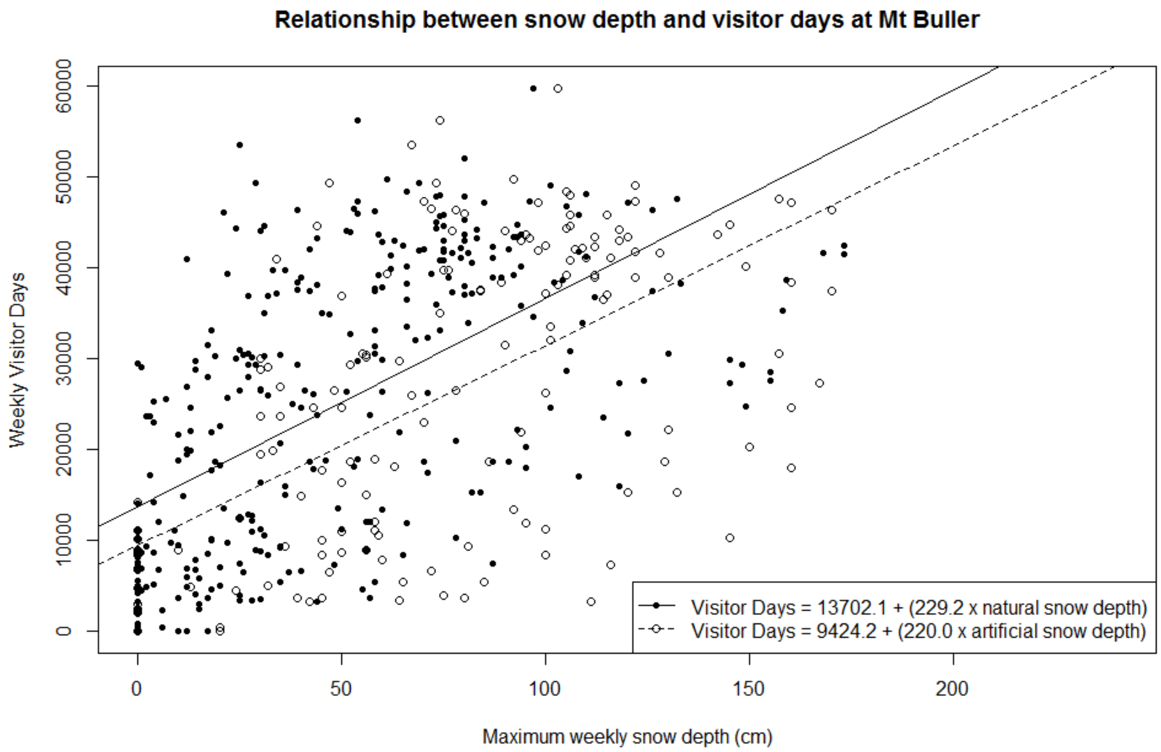


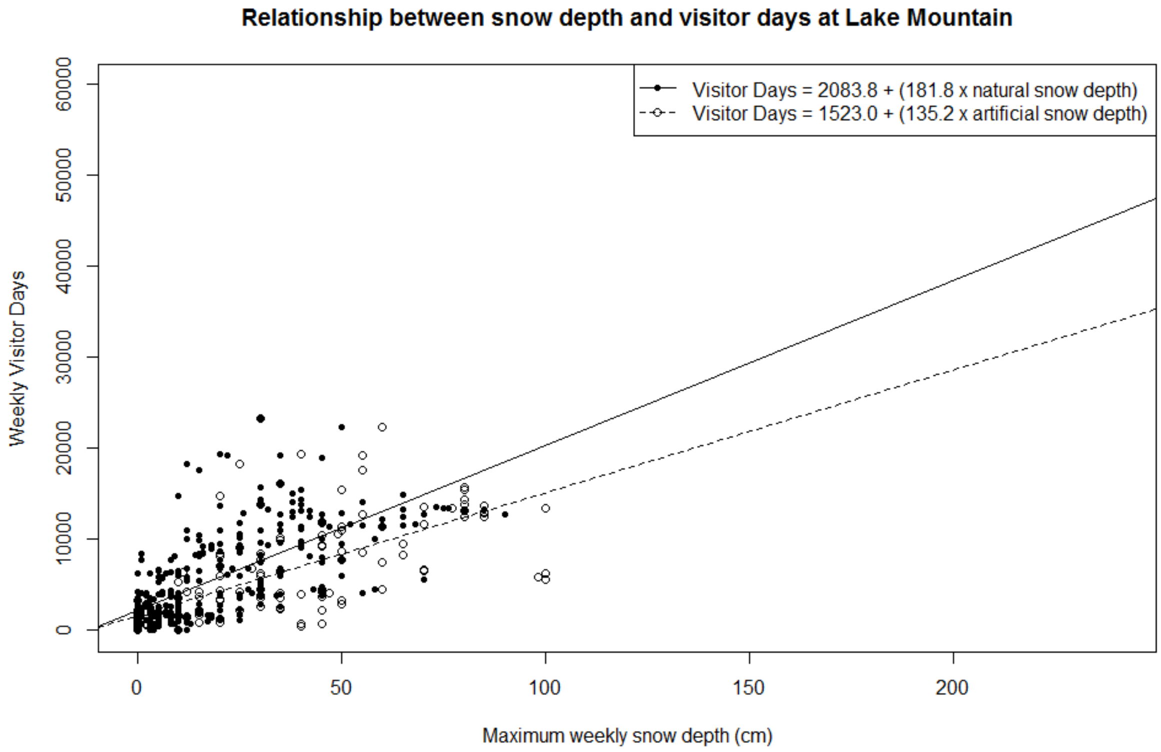
Relationship between snow depth and visitor numbers at Mt Stirling

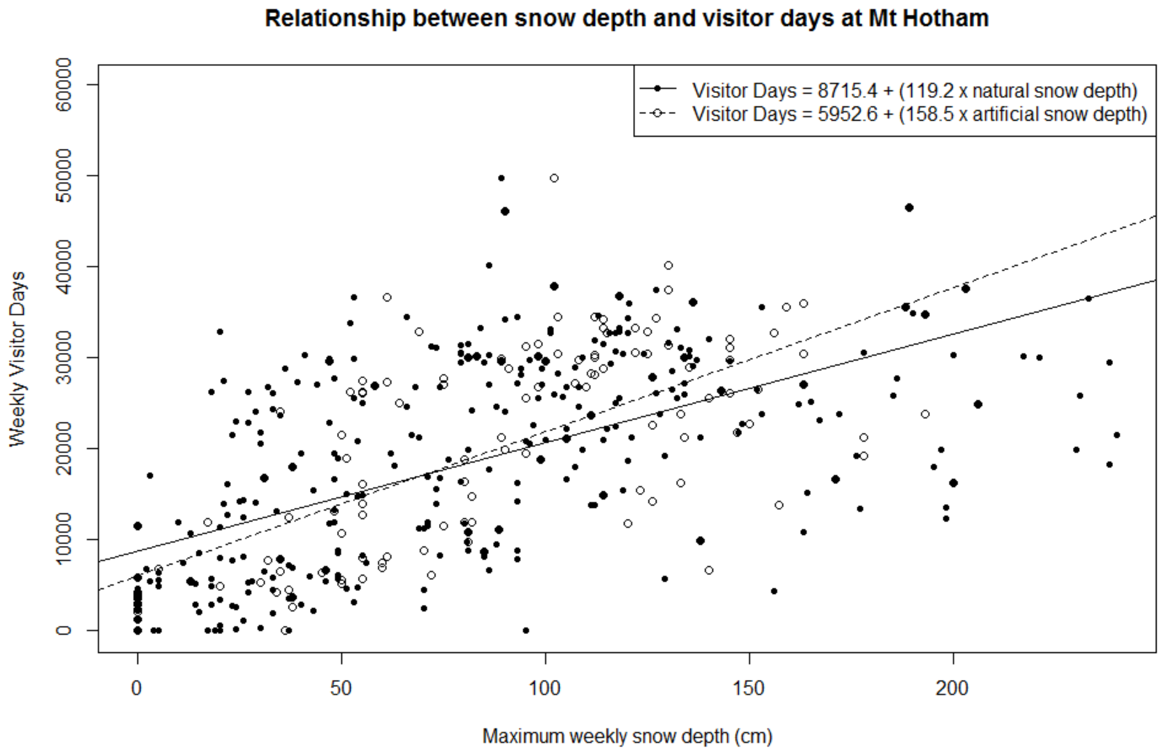


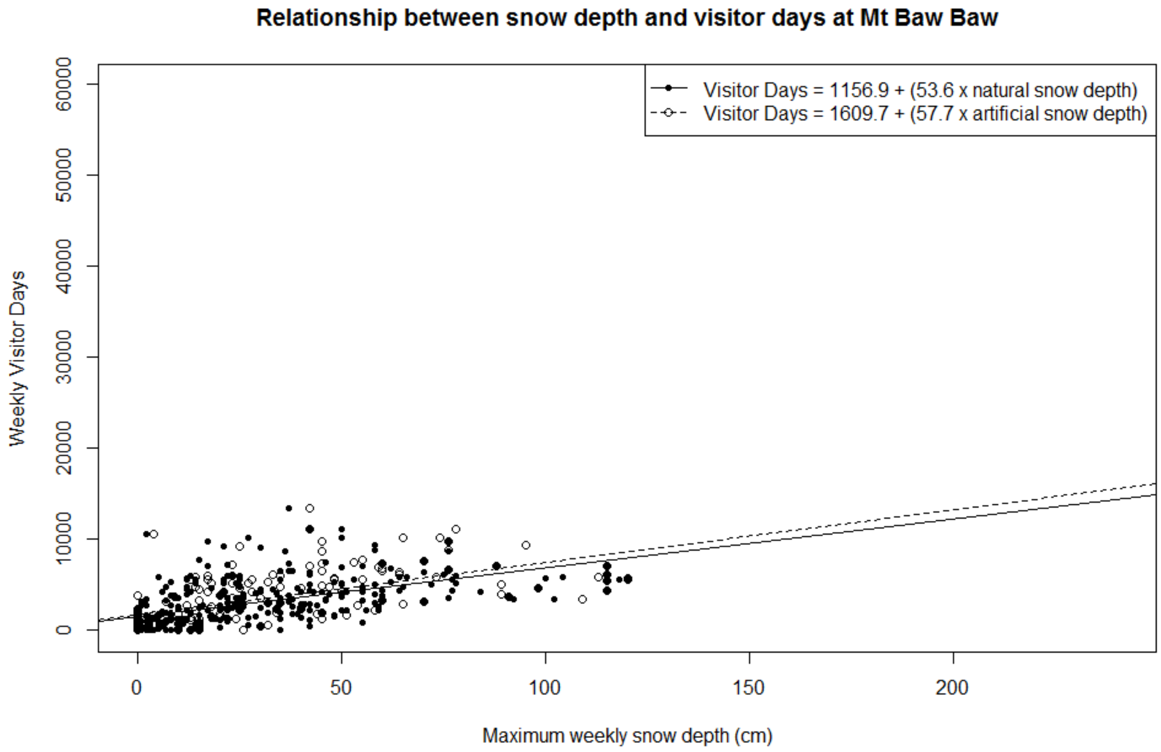
Enlarged figures from Figure 3.4, showing the relationship between maximum snow depth (cm) and weekly visitor days from 1997-2014 at the Victorian alpine resorts. Closed circles represent natural snow depth, open circles represent snow depth in snow-making areas (natural + artificial snow). Lines are linear regressions for natural (solid lines) and artificial snow areas.

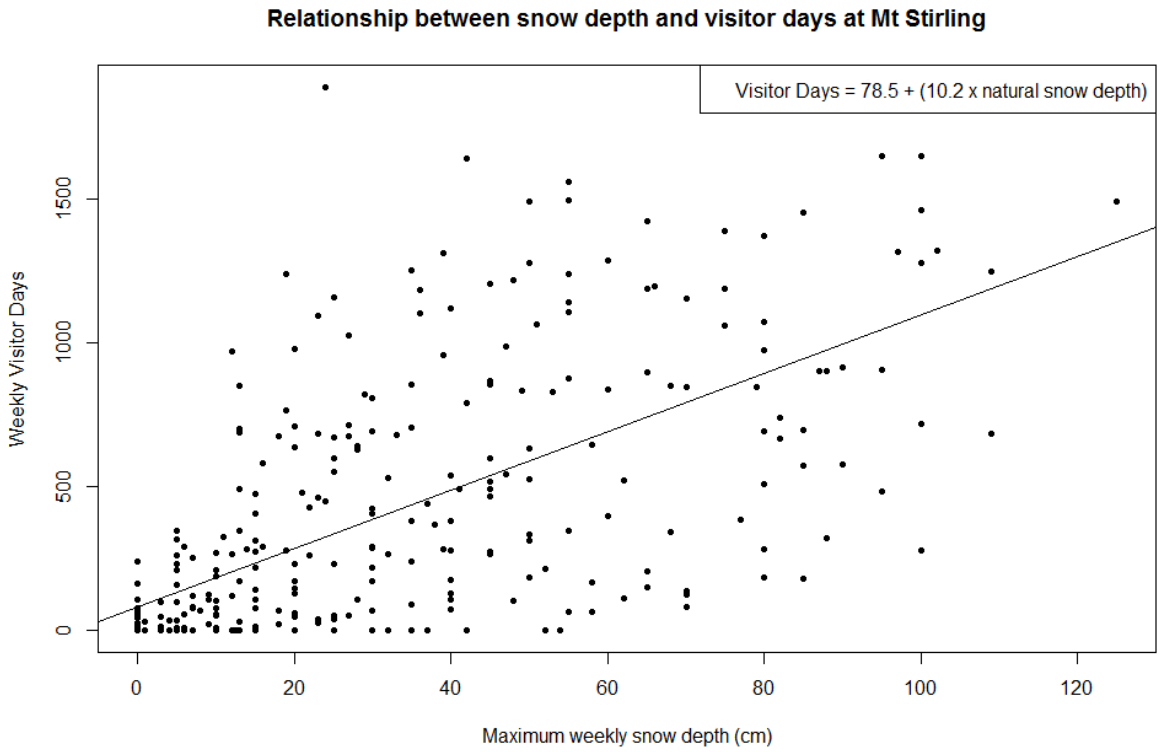





Relationship between snow depth and visitor days at Lake Mountain
Visitor Days = 2083.8 + (181.8 x natural snow depth)
Visitor Days = 1523.0 + (135.2 x artificial snow depth)
Weekly Visitor Days
0
10000
20000
30000
40000
50000
60000
0
50
100
150
200
Maximum weekly snow depth (cm)


Relationship between snow depth and visitor days at Mt Hotham
Visitor Days = 8715.4 + (119.2 x natural snow depth)
Visitor Days = 5952.6 + (158.5 x artificial snow depth)
Weekly Visitor Days
0
10000
20000
30000
40000
50000
60000
0
50
100
150
200
Maximum weekly snow depth (cm)


Relationship between snow depth and visitor days at Mt Baw Baw
Visitor Days = 1156.9 + (53.6 x natural snow depth)
Visitor Days = 1609.7 + (57.7 x artificial snow depth)
Weekly Visitor Days
0
10000
20000
30000
40000
50000
60000
0
50
100
150
200
Maximum weekly snow depth (cm)


Relationship between snow depth and visitor days at Mt Stirling
Visitor Days = 78.5 + (10.2 x natural snow depth)
Weekly Visitor Days
0
500
1000
1500
0
20
40
60
80
100
120
Maximum weekly snow depth (cm)

Part II: Climate change in the Australian Alps region

3.0 Climate projections for the Australian Alps region

Summary

The new projections for the high emissions scenario show that by the end of the century (2070-2099, relative to 1961-1990):

- Average temperatures across the Australian Alps could increase by 4-5°C;
- The greatest increase in mean temperature will occur at the higher altitudes and inland from the coast;
- Changes in temperature and precipitation vary across the region and seasonally;
- Increases in mean daily minimum temperature of up to 6°C may occur at the highest peaks in winter;
- The greatest increases in daily maximum temperature tend to occur in spring, with increases of 5-6°C across much of the Victorian Alps region;
- Annual precipitation may decline by 5 to 20% across the Alps region;
- The greatest declines in precipitation tend to occur in the northern Alps region around Mount Perisher, and at higher altitudes;
- There are declines in precipitation in winter, autumn and spring (up to 10% in each season), and increases in summer precipitation (up to 20%);
- The maximum extent of snow contracts upslope so that snow occurs only on the very highest peaks.

3.1 Introduction

The Climate Futures for the Australian Alps (CFA) projections have recently been completed as part of the Landscapes and Policy Hub (http://www.nerplandscapes.edu.au/). They are unique, fine-scale (5 km) regional climate projections which provide simulations of the evolving state of the climate at a daily level for the periods 1961-2010 and 2070-2099.

The projections simulate fine-scale meteorological processes and include information about topography and land surface conditions (e.g., surface height, coastlines, lakes, and land cover), so they have the ability to show the effect of these factors on regional climate and the climate change signal (Harris et al. 2014). This is particularly relevant in the Alps region, which has a complex topography and a range of regional climate influences.

Six global climate models from the Coupled Model Intercomparison Project archive (CMIP5) were dynamically downscaled using the Conformal Cubic Atmospheric Model (CCAM), developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The host models were: ACCESS-1.0, CCSM4, CNRM-CM5, GFDL-CM3, MPI-ESM-LR and NorESM1-M. The high emissions scenario (RCP8.5) was used, because global emissions are currently tracking at the higher level of this scenario (Peters et al. 2013). If climate change mitigation policies are successful in reducing global greenhouse gas emissions, the projected change would be similar in nature but lower in magnitude.

Previous studies of the potential impacts of climate change on snow in Australia (Whetton et al. 1996, Hennessy et al. 2008) have relied on snow melt-accumulation models based on a simple temperature-index approach, combined with topographic information to estimate snow cover. In contrast, the regional climate model (CCAM) incorporates small scale processes of snow physics, which determine snow accumulation and ablation (melting and evaporation) at the local scale.

An overview of the climate projections for the South-east Australian region is presented in this section. The projected change in precipitation, snow cover and temperature are calculated between the baseline period (1961-1990) and the end of century (2070-2099), and presented as the multi-model mean and range of the six climate models. Resort-specific analyses of the projected changes in snow and snow-making conditions in the early to mid-century are presented in the following section.

3.2 Temperature

The Australian Alps have warmed at a rate of about 0.2°C per decade over the past 35 years (Hennessy et al. 2003). This is twice the rate of warming that has been observed over Australia (Nicholls and Collins 2006). Average temperatures across the Australian Alps region are projected to increase by 4-5°C under the high emissions scenario considered here (RCP 8.5) (Figure 3.1). These rates of increase are higher than the observed and projected increases in the global mean temperature (observed increase 0.12 °C per decade since 1951; projected increase 2.6-4.8°C relative to 1986-2005, RCP8.5 (IPCC 2014)).

The six models show a range of temperature change between the baseline and future periods (Table 3.1). The mean change in minimum daily temperature across the domain ranges from 3.4°C to 5.0°C, while the range in maximum daily temperature is from 3.0°C to 6.1°C.

There is a strong gradient in projected temperature change associated with altitude, and also with distance from the coast. The greatest increases in mean temperature occur at the higher altitudes. Daily maximum and minimum temperatures show a similar pattern of increase (Figure 3.2), although the increase in minimum temperatures appears to be moderated by coastal influences to the south in these simulations.

Table 3.1: Range in temperature change projected to occur between the baseline period (1961-1990) and end of the century (2070-2099) by the six climate models. Means are for all grid cells in the domain above 500m elevation.

Climate model	**Change in Mean Minimum Daily Temperature (°C)**	**Change in Mean Maximum Daily Temperature (°C)**
ACCESS1-0	4.3	4.8
CCSM4	4.2	4.1
CNRM-CM5	3.6	4.1
GFDL-CM3	5.0	6.1
MPI-ESM-LR	4.1	4.7
NOR-ESM1-0	3.4	3.0

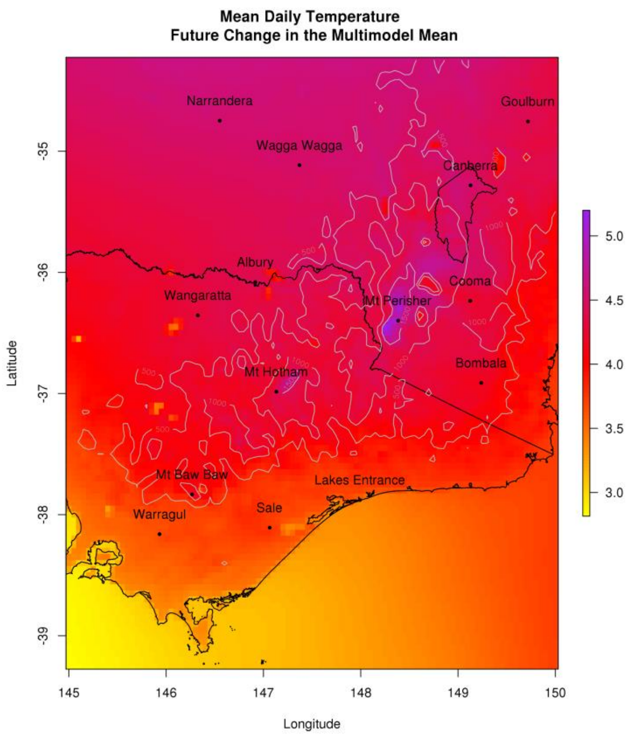


Figure 3.1: Change in mean daily temperature (°C) across South Eastern Australia between the baseline period (1961-1990) and end of the century (2070-2099), based on the multi-model mean of the six downscaled climate models.

a) b)

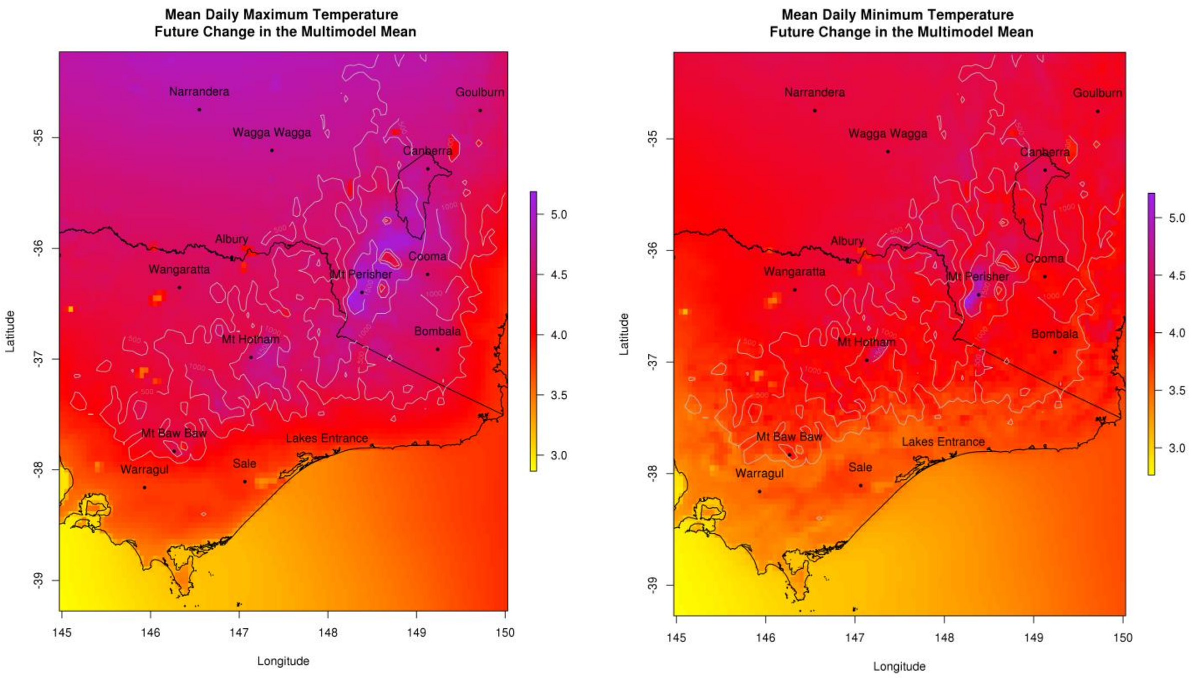


Figure 3.2: Change in a) mean daily maximum temperature and b) mean daily minimum temperature (°C) across South Eastern Australia between the baseline period (1961-1990) and end of the century (2070-2099), based on the multi-model mean of the six downscaled climate models.

Projected changes in temperature show strong spatial and seasonal variability, with more spatial variation in the change in temperature in each season than in the annual change (Figures 3.3 and 3.4). In winter, the greatest increases in mean daily minimum temperature, up to 6°C, are projected to occur at the highest peaks, particularly around Mt Hotham and Mt Perisher (Figure 3.3). In autumn, the change in minimum temperature is more even across the Alps region, with projected increases of 3.5-5°C. The coastal influence causes milder temperature increases, particularly in spring, when increases in minimum temperatures are approximately 3°C along the coast, compared to increases of 3.5-5°C across most of the Alps, and up to 6°C in the northern Alps and at Mt Perisher. In contrast to the coast, inland temperatures are generally higher and show the greatest change. The temperature difference between continental areas and the oceans has been observed to be increasing in recent years, and is one line of evidence of the signal of rising greenhouse gases (Bindoff et al. 2013).

The greatest increases in daily minimum temperatures (more than 6°C) are projected to occur in summer, on the western side of the Alps, reflecting the influence of the hotter westerly winds coming from the interior of the Australian continent.

In contrast to the daily minimum temperatures, the greatest changes in daily maximum temperature are projected to occur in spring (Figure 3.4). Increases of more than 6°C are projected for the more northern parts of the Alps, including Mt Perisher, and 5-6°C across much of the Victorian Alps region. Summer temperature increases are more even across the region compared to minimum temperatures, suggesting that regional differences in diurnal temperature range may occur. In winter, there is a strong gradient in change, with greater warming in maximum temperature (3.5-5°C) on the eastern side of the Alps range. This is consistent with the presence of a Föehn wind effect, leading to warmer temperatures and lower relative humidity in the air coming over the mountains from the west. Alternatively, the temperature gradient could be caused by changes to the westerly circulation or local effects due to the drying climate and snow loss.

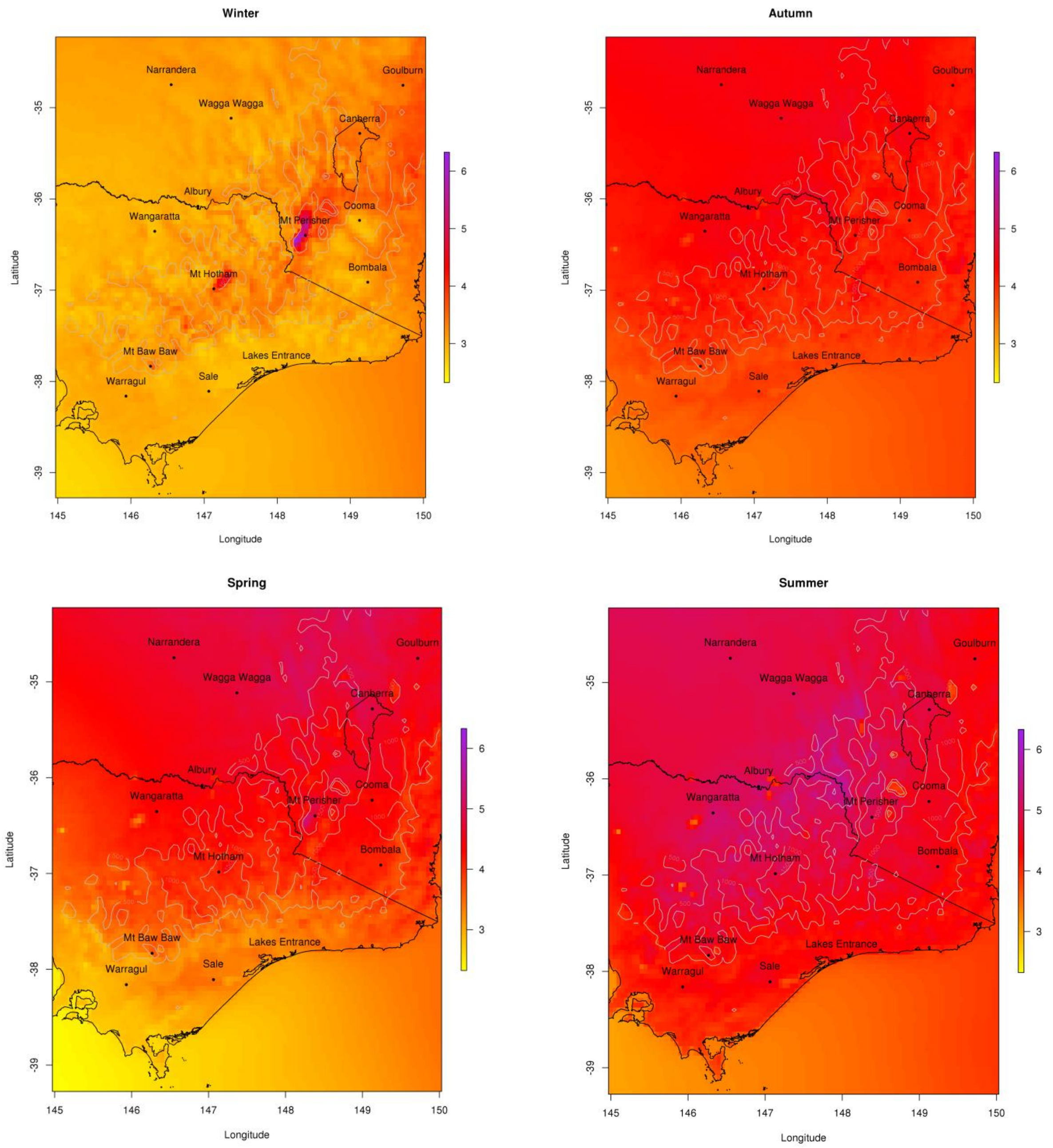


Figure 3.3: Change in seasonal mean daily minimum temperature (°C) across South Eastern Australia between the baseline period (1961-1990) and end of the century (2070-2099), based on the multi-model mean of the six downscaled climate models.

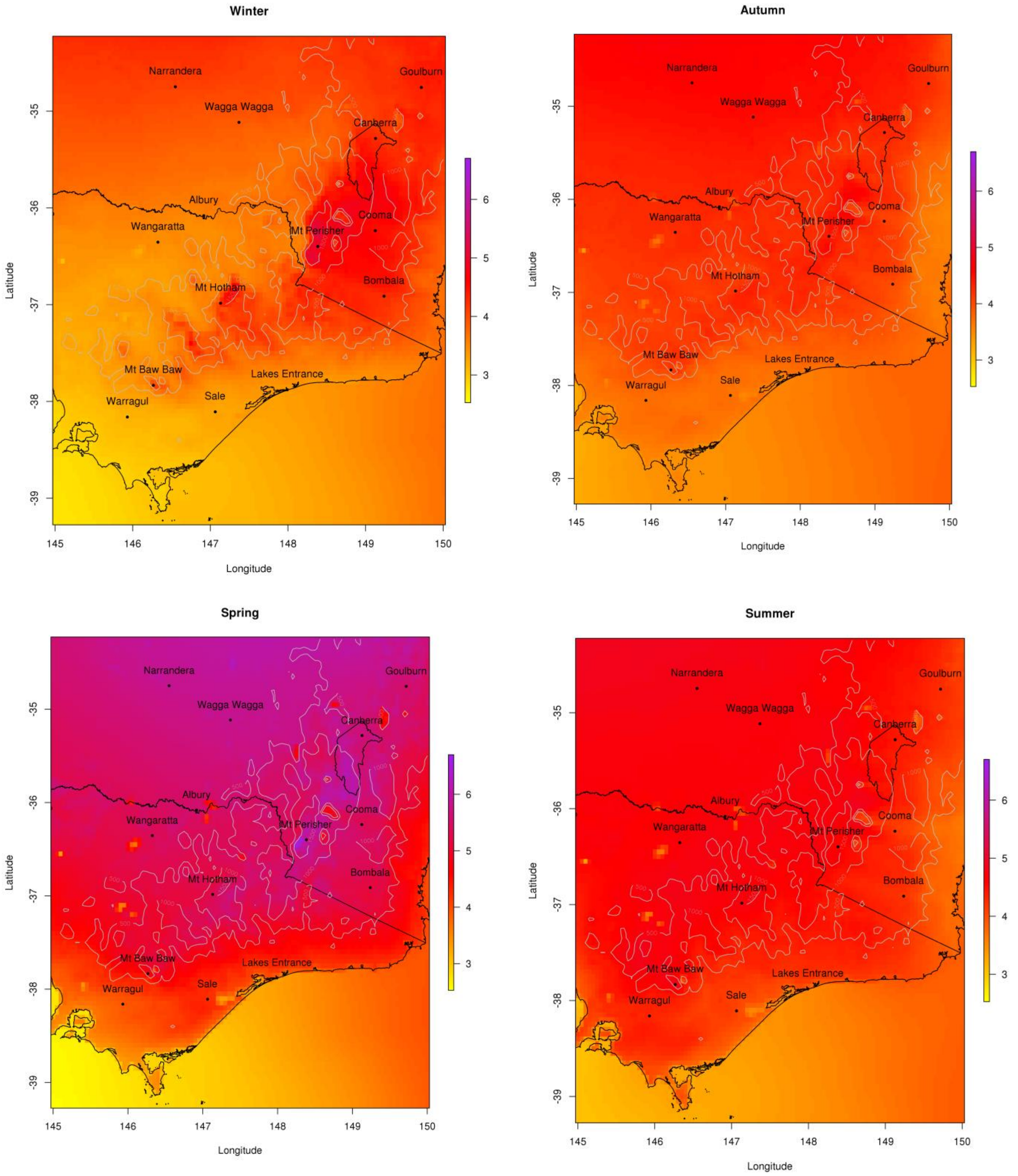


Figure 3.4: Change in seasonal mean daily maximum temperature (°C) across South Eastern Australia between the baseline period (1961-1990) and end of the century (2070-2099), based on the multi-model mean of the six downscaled climate models.

3.3 Precipitation

Precipitation (rainfall and snow) from the multi-model mean is projected to decline across the Alps by 5 to 20% by the end of the century under the high emissions scenario (Figure 3.5).

As with temperature, there are seasonal and regional differences in the pattern of precipitation change (Figure 3.6). The greatest decreases in annual precipitation are projected to occur in the north around Mt Perisher, and at higher elevations across the Alps. Seasonally, reductions in precipitation are projected to occur in autumn, winter and spring, with approximately 10% reduction per season. In summer, however, increases in precipitation of up to 20% are projected to occur across most of the region. There are some localised areas where there may be no change to summer precipitation, such as Mt Baw Baw in Victoria and Mt Perisher in NSW. The increase in precipitation in summer is not sufficient to offset the declines in the other seasons, resulting in the annual decline shown in Figure 3.5.

The projected changes in precipitation in the multi-model mean are very significant and broadly consistent with our understanding of the large scale drivers of the weather and climate in the Australian region, such as the poleward shift in winter storm tracks (Frederiksen and Frederiksen 2007) and the subtropical ridge (Grose et al. In Press), and changes to blocking high pressure systems (Risbey et al. 2013). However, there are large differences between the climate models, leading to a broad range of plausible future projections of rainfall (Table 3.2). The mean change in precipitation across the domain ranges from a decrease of -15.7% to an increase of 13.0%, although all models project reduced rainfall at altitudes greater than 1200m. This degree of uncertainty is common in projections of rainfall (CSIRO and Bureau of Meteorology 2015), because the large-scale storm tracks in the projections are uncertain (Risbey and O'Kane 2011), and it is difficult to fully resolve the many physical processes involved in precipitation or the fine-scale spatial variability (Dowdy et al. 2015).

Table 3.2: Change in precipitation projected to occur between the baseline period (1961-1990) and end of the century (2070-2099) by the six climate models. Values are given for all grid cells in the domain above 500m elevation.

Climate model	**Precipitation Change (%)**
ACCESS1-0	-5.6
CCSM4	5.0
CNRM-CM5	-7.1
GFDL-CM3	-15.7
MPI-ESM-LR	-5.6
NOR-ESM1-0	13.0

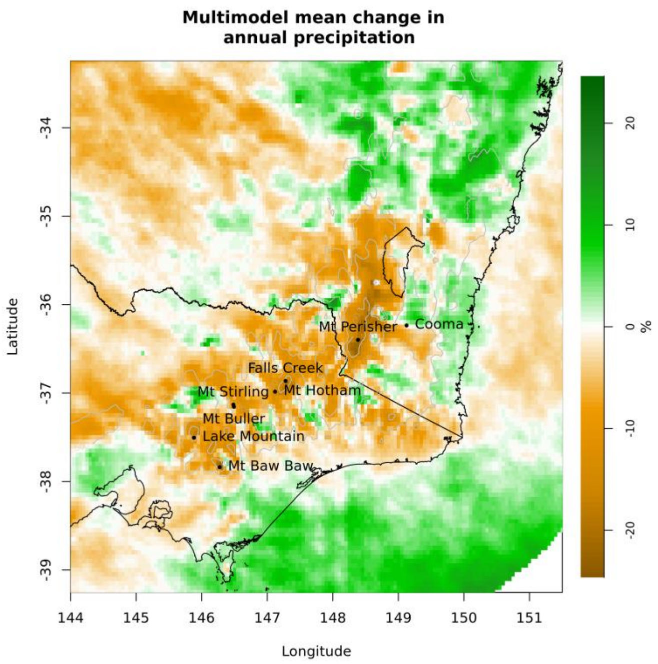


Figure 3.5: Change in mean annual precipitation across South Eastern Australia between the baseline period (1961-1990) and end of the century (2070-2099), based on the multi-model mean of the six downscaled climate models.

3.4 Snow cover

The projected change in the maximum extent of snow within seven 10-year time periods is presented in Figure 3.7. The maximum extent is the sum of all grid cells from any of the six climate models with any snow at all in each decade. The projections of snow extent reflect the declines in maximum snow depths that have already been recorded at Australian alpine resorts since the 1950's (Bhend et al. 2012). Since the 1960's, the projections show a steady reduction in snow cover across the Alps, particularly at lower elevations. By the end of the 21st century the maximum extent of snow is projected to have contracted so that only the very highest peaks, such as Mt perisher and Falls Creek, experience any days with snow. There is a range in snow volume projected across the six models, but all show a substantial decline in snow volume across the Alps region, and a contraction in the length of the ski season. Figure 3.8 illustrates the contraction in snow extent over time, and enlarged figures can be found in Appendix A.

Quantitative validation of the model output is difficult in the absence of long-term measurements of snow cover and depth across a range of representative sites. However, the CFA outputs for snow cover produce similar qualitative patterns in snow cover as calculated by previous authors using different methods (eg. satellite data covering the period 2000–2010 (Bormann et al. 2012), and modelled simulations (Whetton et al. 1996, Bhend et al. 2012)).

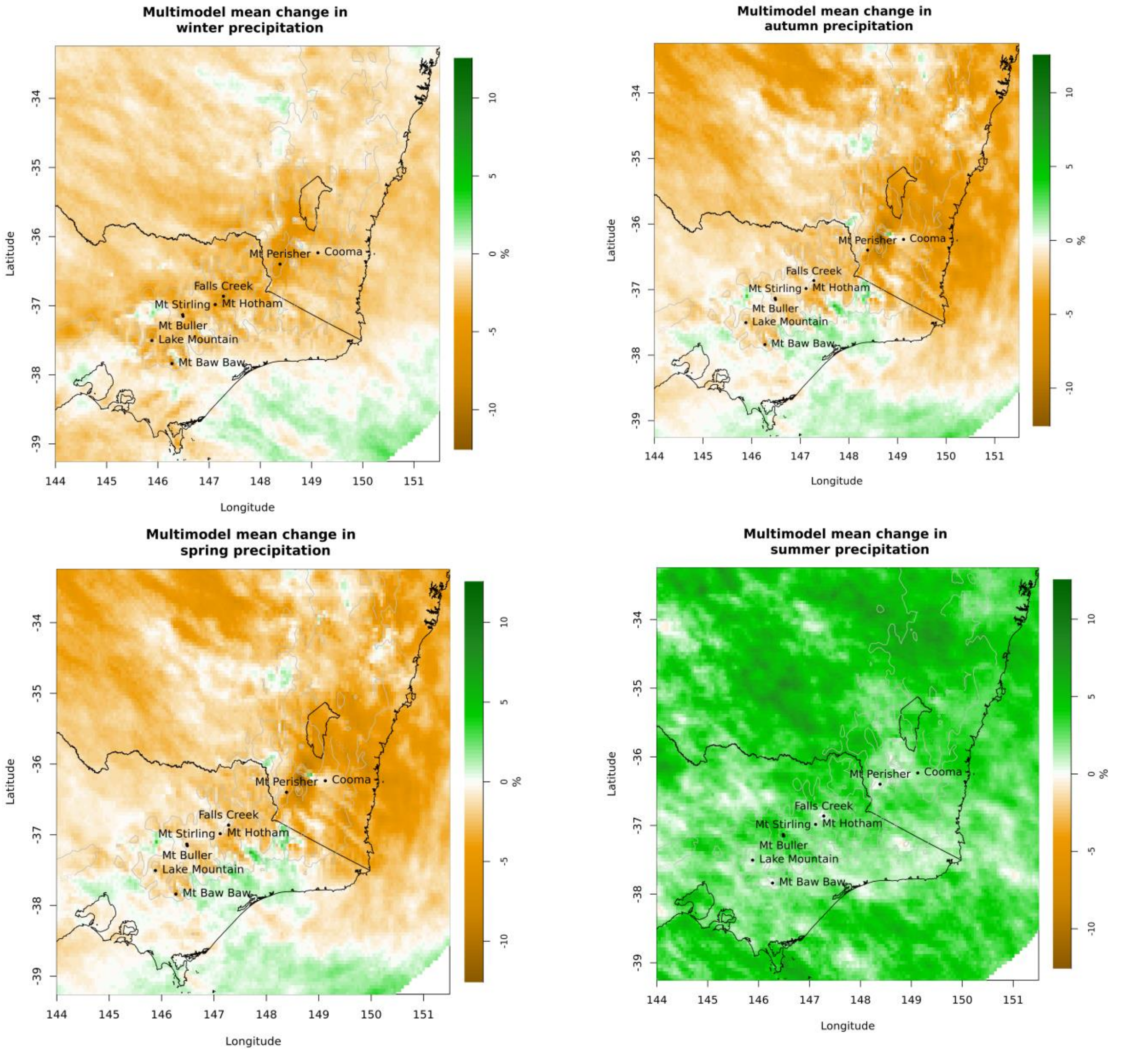


Figure 3.6: Change in seasonal precipitation across South Eastern Australia between the baseline period (1961-1990) and end of the century (2070-2099), based on the multi-model mean of the six downscaled climate models.

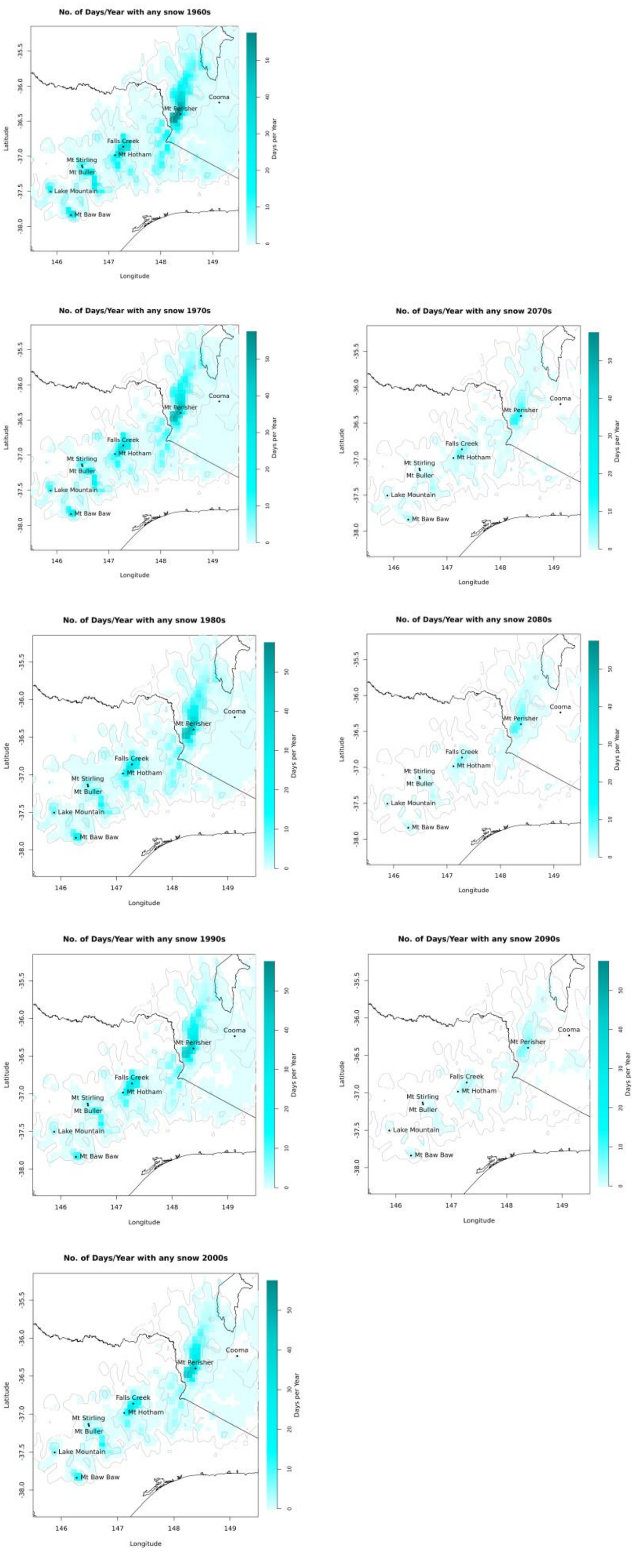


Figure 3.7: Maximum extent of snow projected over the Australian Alps for past and future time periods, shown as all grid cells with any snow at all in each decade from any of the six climate models. Enlarged figures are provided in Appendix A (Part II).

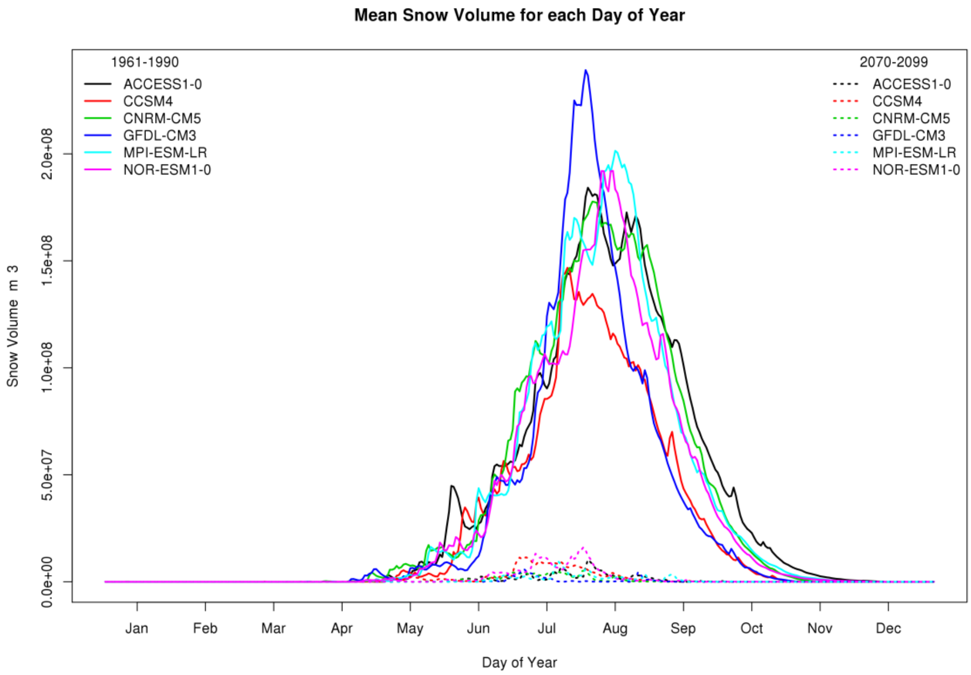


Figure 3.8: Mean volume of snow per day projected by six climate models over the Australian Alps region for past and future time periods.

3.5 Conclusions

Increases in mean temperature of 4-5°C and reductions in precipitation of 5 to 20% are projected to occur over the Alps region by the end of the century under a high emissions scenario (RCP8.5). These changes vary seasonally and across the south east Australian region. Snow cover and volume will decline to the extent that eventually only the highest peaks will experience any snow. These changes are likely to have a large impact on natural ecosystems and recreational use in the region.

The Climate Futures for the Australian Alps projections provide regional details of climate change between the baseline period (1961-1990) and the end of the century. These give an indication of the trajectory of change, but further analysis is required to highlight the rate of change over the next few decades. Targeted analysis of climate change at individual resorts could take advantage of the fine temporal and spatial resolution of the CFA projections, to identify the seasonal and decadal trends in temperature, precipitation and snowfall, as well as specific requirements for snow-making.

4.0 Changes projected to occur at the Victorian Alpine Resorts between current and future time periods

Summary

Significant changes in climate are projected for the Victorian Alpine Resorts under ongoing climate change. Under a high emissions scenario, the resorts are expected to experience rising temperatures (~4°C), decreased Winter precipitation, and reductions in natural snowfall of between 60% and 80% (by 2070-2100, relative to 1961-1990). The results show a contraction in the duration of the ski season based on natural snow, with a later start and earlier finish relative to the modelled historical period (1960's).

As natural snow declines, more snow will need to be made, under warmer conditions, to achieve the target snow depth profiles throughout the season. The number of hours suitable for snowmaking before the start of the ski season is projected to decline substantially at all resorts. There is a gradual decline from 1960 to 2000, superimposed on large year-to-year variability, followed by a marked drop in available hours for snowmaking between the 2020's and 2030's. Relative to the 2010's, opportunities for snowmaking are halved by 2030 at all resorts, with the exception of Falls Creek where opportunities halve by 2040's.

If snow is made at warmer temperatures, opportunities for snowmaking may be able to be maintained at current (2010) levels until the 2030's (-1°C wet bulb temperature), or until 2080-2090 if snow can be made at -0.5°C wet bulb temperature. However, making snow at warmer temperatures may be associated with trade-offs in cost and quality of snow.

The new projections confirm previous research by CSIRO that demonstrated reductions in natural snowfall and contractions in season length based on both natural snow and opportunities for artificial snowmaking (Whetton et al. 1996, Hennessy et al. 2008, Bhend et al. 2012). In line with previous work, the current work suggests that climate change impacts are not only a challenge for the future, but are already impacting the Victorian alpine resorts.

4.1 Introduction

Several studies have assessed recent changes in temperature and snow cover across the Victorian alpine region and investigated changes to natural snow cover under future climate conditions (described in detail in Part I of this report). Hennessy et al. (2008) assessed recent changes in temperature and snow cover across the Australian alpine region and estimated changes in natural snow cover and depth for 2020 and 2050 using the CSIRO snow model (Whetton et al. 1996). They also assessed the extent to which snowmaking may be able to offset reduced natural snow cover. The study concluded that “with sufficient investment in snow guns, the Australian ski industry may be able to manage the effect of projected climate change on snow cover until at least 2020.” (Hennessy et al. 2008 pg 255).

The most recent report focussing on Victoria’s alpine resorts (Bhend et al. 2012) confirmed the results from previous studies, that natural snow cover and depth will continue to decline under projected climate change, and the ski season will start later and finish earlier than in the past. The number of good seasons is expected to decline as the number of poor seasons increases. However, precipitation and snow season length is highly variable across years at high elevations (Bormann et al. 2012), so that good seasons may still occur in the short to medium time scales. This highlights the need to pay more attention to daily, monthly and annual variability in natural snow cover and snowmaking conditions (Bhend et al. 2012), rather than focus only on climate projections averaged over 20-year periods. Such information will assist resort managers plan for changing climate conditions and develop robust climate adaptation plans.

Snowmaking is an important part of Victoria’s resort management and is likely to play an increasing role as the alpine resorts adapt to declining natural snow cover. It is used to guarantee the season start, extend the season duration, and maintain the viability of heavily used and lower altitude slopes. In 2006, for example, a year with very low natural snow cover, snowmaking increased the number of days with snow cover greater than 30cm from 32 to 105 days at Falls Creek; from 0 to 75 days at Mt Buller; from 35 to 94 days at Mt Hotham; and from 0 to 32 and 70 days at Lake Mountain and Mt Baw Baw respectively (Pickering 2011). The three lowest resorts were therefore only able to open in 2006 because of snowmaking (Pickering 2011).

This study was designed to investigate the potential impacts of climate change on Victorian alpine resorts. This section includes:

1. An assessment of the changes projected to occur in temperature, precipitation and snow cover, between the baseline (1961-2010) and end of century (2070-2099) time periods, at each of the six Victorian alpine resorts (Falls Creek, Lake Mountain, Mt Baw Baw, Mt Buller, Mt Hotham and Mt Stirling);
2. An assessment of shifts in the timing and duration of the ski season based on natural snowfall; and

3. An analysis of variability in snowmaking conditions and changes in the frequency of suitable snowmaking conditions under future climate conditions.

This analysis adds to previous work with the use of daily data to improve estimates of within and between year variability in snow cover and estimates of the proportion of precipitation falling as snow. In addition to projections of mean temperature, we assess changes to daily wet bulb temperatures, to refine estimates of the frequency of conditions suitable for snowmaking. The results are discussed in the context of the uncertainty associated with projections of future climate. This is particularly relevant to projections for the Australian Alps region, where the topography and very high annual variability in precipitation (Fiddes et al. 2015) present challenges to modelling future climate conditions.

An overview of the methodology and results across all Victorian resorts is presented first, followed by detailed results for each resort in separate sections.

4.2 Methods

The six alpine resorts in Victoria cover a range of elevations and terrain, have different facilities and snowmaking infrastructure, and offer different visitor experiences. The higher altitude resorts, Mount Buller, Falls Creek and Mount Hotham, receive the majority (70-80%) of ski field visitors. At these resorts natural snow is both more likely and more persistent, and there is greater capacity for snowmaking. Lake Mountain and Mount Stirling have no downhill ski infrastructure or accommodation, and instead cater to “snow-play” and cross country skiing.

Consultation with resort operators and the Alpine Resorts Coordinating Council (ARCC) identified the key climate variables that determine natural snowfall and influence the ability of the resorts to make and retain snow. These were dry bulb temperature, wet bulb temperature, precipitation, snowfall, the proportion of precipitation falling as snow and wind speed and direction. Some variables were identified as being important but could not be considered here because they are not available as model output (eg. temperature of stored water used for making snow at the beginning of the season).

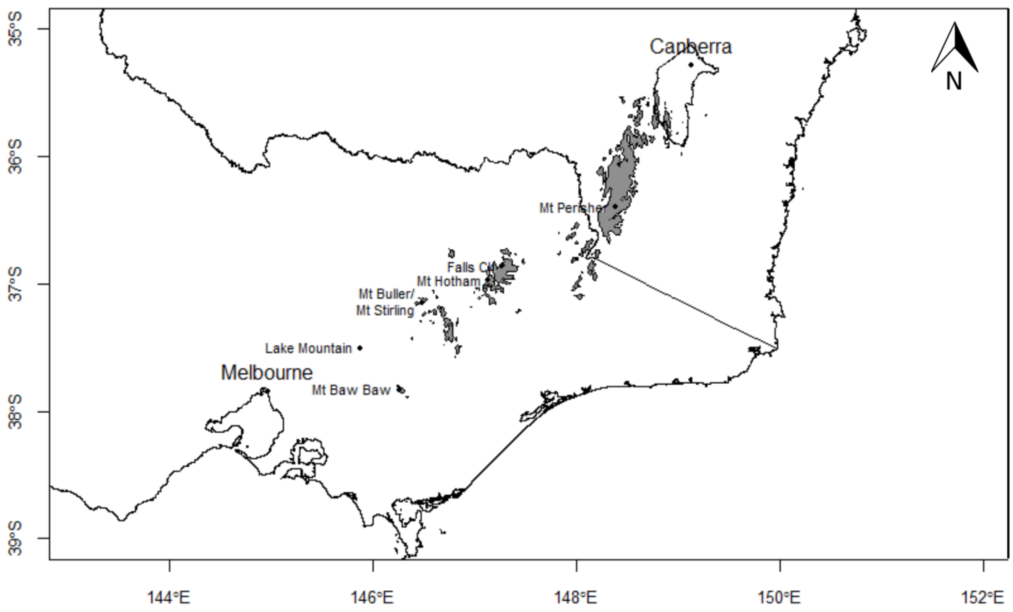


Figure 4.1: Locality of the Victorian alpine resorts. Grey areas are those elevations above 1400m (based on a 9sec Digital Elevation Model), which would historically have been snow-covered for at least 1 month per year (Hennessy et al. 2008).

4.2.1 Climate Futures for the Australian Alps projections

The Climate Futures for the Australian Alps (CFA) projections provide daily climate data for the periods 1961-2010 and 2070-2099. These two time periods enable the model output to be validated against recent observations, and the changes projected to occur between the current period and the end of the century to be assessed. An understanding of inter-annual variability in climate under current and future conditions is also possible. However, data covering the decades 2010 to 2070 are not available as direct model output. This information is essential for adaptation planning, so a statistical approach has been applied to interpolate the trends during the time period 2010 to 2070.

The statistical approach used (See Box 2) is based on the assumption that the trend occurs gradually over time. It is therefore considered robust for temperature, which is projected to increase at a relatively constant rate over the coming decades. However, it was not possible to apply this approach to the snow depth or snowfall data, firstly because of the very high variability in these two variables in the near future, and also because the projected values for these variables tend towards zero towards the end of the century. Similarly, the physical processes that determine rainfall are complex and not likely to follow a simple linear trend. For these reasons we do not present values for precipitation or snow depth for the period 2010 to 2070. Running the regional climate model for the intervening years would be required to provide estimates for these variables in the near future, although the high natural variability would remain. Data for the early to mid-century decades (2010 onwards) are instead presented to assess changes to the conditions suitable for snowmaking based on wet bulb temperature (see Section 4.2.2).

Results are presented for six Global Climate Models (GCMs) from the Coupled Model Intercomparison Project archive (CMIP5) that were dynamically downscaled using the Conformal Cubic Atmospheric Model (CCAM), developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The host models were: ACCESS-1.0, CCSM4, CNRM-CM5, GFDL-CM3, MPI-ESM-LR and NorESM1-M. These models give slightly different results because they are based on different configurations, but all represent plausible representations of the future climate. The models cover much of the range in the full CMIP5 archive, although they do not include the very driest models (eg. GFDL-ESM-2M, CMCC-CMS and CSIRO-Mk3.6). The subset of models includes NorESM1-M, which is a low sensitivity model (2.8°C/doubling CO_2) with a low projection for Australia (2.61°C), through to GFDL-CM3, a high sensitivity model (4.0°C/doubling CO_2) with a high projection for Australia (4.79°C).

To incorporate the uncertainty due to the range in climate models (See Box 3), we present the results from the two models that give the highest and lowest value of each variable. The model NorESM1-M projects the lowest temperature increases (approximately 3°C) and an increase in precipitation of 13% by the end of the century. GFDL-CM3 projects the highest temperature increases (approximately 5°C) and the greatest decline in rainfall (-15%) (Table 4.1). This range can be thought of as representing the “best” and “worst” case futures. The multi-model mean is also presented. Averaging the six models smooths out the annual and decadal components of natural variability and reveals the forced climate response independent of the different model configurations (See Box 3).

The high emissions scenario (RCP8.5) is used because global emissions are currently tracking at the higher level of this scenario (Peters et al. 2013). If strong mitigation policies were to achieve reductions in global greenhouse emissions, the pattern of projected changes would be similar, but lower in magnitude.

Table 4.1: Range in mean precipitation, minimum and maximum temperatures for projections over south eastern Australia across the six climate models. Values are the change between the baseline (1961-1990) and end of the century (2070-2099) periods. Means are for all grid cells in the domain above 500m.

Climate model	% change in Precipitation	Change in Minimum temperature (°C)	Change in Maximum temperature (°C)
NorESM1-M	+13	3.0	3.4
CCSM4	+5	4.1	4.2
MPI-ESM-LR	-5	4.7	4.1
ACCESS-1.0	-5	4.8	4.3
CNRM-CM5	-7	4.1	3.6
GFDL-CM3	-15	6.1	5.0

Box 1 – Making snow in the Victorian Alpine resorts

Snowmaking has been used for many years in the Victorian Alpine resorts to guarantee the season start, extend the season duration, and maintain the viability of lower altitude slopes.

Two main snowmaking systems are used. The most widely applied system uses snow guns (fan, air/water and lance guns) to make snow across large areas. Snow guns produce snow by breaking up a stream of water into fine particles and then propelling these into the atmosphere under conditions that cause them to freeze as particles of snow. The efficiency of snow guns is largely determined by the combination of low temperatures and low humidity (described by the wet bulb temperature). Generally, good quality snow can only be made at wet bulb temperatures lower than -2°C. However, if the humidity is low, snow can be made at higher ambient temperatures. Recent improvements in technology, such as computer controlled air/water mixing and automation of start-up, have greatly improved the energy efficiency of snowmaking, and improved snow quality and reliability. At times, snow has been made at the Victorian resorts at temperatures as warm as -0.4°C wetbulb.

Snow is made at different wet bulb temperatures across the resorts, reflecting the range in requirements and conditions under which each resort operates. Different elevations and type of ski activities determine the quality of snow needed at different times of the year. Trade-offs in snow quality and cost at less optimal conditions will therefore differ across the resorts. Start-up temperatures for snowmaking across the Victorian resorts currently range from –0.7 to -1.0°C (Lake Mountain) to -1.5°C (Mt Buller). Each resort also has a range of different conditions, such as slope, aspect and vegetation cover, and apply a range of grooming processes which affect the ability to make and retain snow throughout the season.

The second snowmaking system, the Snow Factory, has been in use since 2014. This system is used to cover relatively small areas or for particular events. The Snow Factory can make snow at any temperature, as it uses cooling technology to freeze water and spread it as small dry ice flakes.

This report addresses the climate conditions required for Snow guns, since the limitations of the Snow Factory (eg. availability and cost of water and energy) are not weather dependent. We summarise trends in wet bulb temperatures of -2°C, -1°C and 0.5°C to cover improvements in technology, and the trade-offs in cost and snow quality that might be considered at different times and resorts.

Box 2 - Statistical method to fill in the period 2010-2070

A periodic Seasonal and Trend decomposition using a Loess procedure was used to estimate the missing values between the current and future time periods (2010-2069) at each resort. This method estimates the seasonal component using Loess smoothing of the seasonal sub-series (the series of all values for each month). The seasonal values are removed, and the remainder smoothed to find the trend. The remainder component is the residuals from the seasonal plus trend fit.

The term “loess” is an acronym for “local regression”. Loess is a simple strategy for fitting smooth curves to empirical data. It is nonparametric in that it does not require any prior understanding of the relationship between the dependent and independent variables. Instead, the fitting algorithm simply tries to follow the empirical concentration of the plotted points.

The loess procedure can be conceptualized as a “vertical sliding window” that moves across the x axis of a scatterplot (time in the current time series analysis). The window stops and estimates a separate regression equation (using weighted least squares) at each step. Since the regressions only involve the data points that fall within the window, the estimated slopes can change to follow the contours of the data.

The statistical method is based on three assumptions: 1) There is a simple linear trend between the average of the historical period and the future period; 2) The seasonal component of the variability does not change in magnitude through time; 3) The magnitude of random variability does not change over time.

A linear trend was applied between the historical mean (1960-2010) and the future mean (2070-2100). The seasonal and random components of variability identified by the Loess Decomposition were then added to the trend to infer the missing values between the current and future periods.

The full time series of wet-bulb temperature, from 1961-2100, for each resort, is presented in Appendix C, Part II.

Box 3 - Sources of uncertainty in projections of future climate

There will always be uncertainty associated with projections of future climate, due to:

1. uncertainty about future global greenhouse emissions;
2. the range in projections from different climate models; and
3. the internal variability of the climate system (eg. weather events, El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO).

The relative importance of each of these sources of uncertainty differs at different time scales. In the short term, internal variability and range in climate models will contribute the most uncertainty. These sources of uncertainty also increase at smaller spatial scales. In the longer term, the dominant sources of uncertainty are those associated with emissions scenarios and differences between climate models. The relative contribution from internal variability generally declines over time as the signal of climate change strengthens (CSIRO and Bureau of Meteorology 2015).

The Victorian Alpine Resorts are located in a region with strong inter-annual and inter-decadal climate variability. This is particularly the case for precipitation. This variation is likely to be a key influence on how the resorts adapt to climate change over the coming decades.

Internal variability is a key consideration for climate change projections into the 21st century. Separating out responses to internal climate fluctuations from climate change is a key challenge, particularly at regional and near-future time scales. The climate change signal is more likely to be swamped by variability and harder to detect at the regional scale.

Uncertainty will also be greater for some variables. For example, uncertainty is typically larger in projections of rainfall than temperature, because it is difficult to model the many physical processes involved or the fine-scale spatial variability. It is not unusual to get projections for rainfall at a site that range from a decrease to an increase (CSIRO and Bureau of Meteorology 2015). This highlights the need to take into account the range of projections.

However, a comparison of the projected snow reduction across the six climate models suggests that the response is largely driven by temperature. Even those models that project increasing precipitation by the end of the century, NorESM1-M (+13%) and CCSM4 (+15%), show substantial reductions in snow cover (Figure 4.2). This is important in the assessment of uncertainty in the results, because the temperature increases are near certain, whereas the sign of the precipitation change is much less certain.

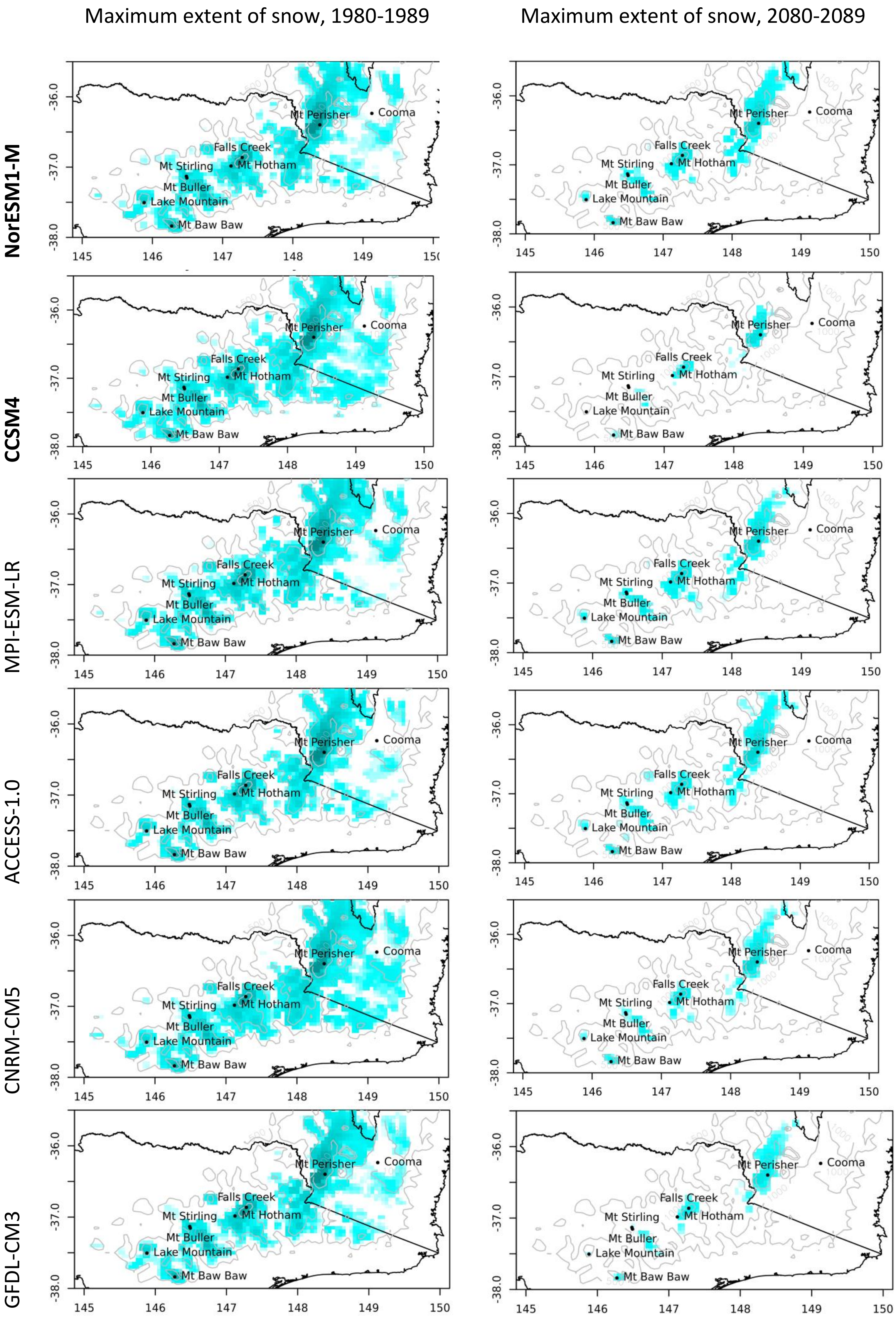


Figure 4.2: Maximum extent of snow projected for the decades 1980-1989 and 2080-2089, calculated as the sum of all grid cells with any snow at all in each decade. All models show substantial reductions in snow cover, including those that project increases in precipitation, NorESM1-M and CCSM4 (indicated in bold).

4.2.2 Wet-bulb temperature

Wet bulb temperature is the lowest temperature that can be reached by the evaporation of water only. It incorporates relative humidity, which determines the temperature at which snow can be made. If relative humidity is very low, snow can be produced at ambient temperatures as high as +4°C (although this is not common in Australia). The critical temperature for traditional snowmaking is a wet bulb temperature of approximately -2°C, but more recent snowmaking approaches enable snow to be made at higher temperatures (see Box 1). For this reason we present results for the number of hours below thresholds of -2°C, -1°C, and 0.5°C wet bulb temperature.

Wet-bulb temperature was calculated from the 3 hourly data for dry-bulb temperature (bias-adjusted against gridded Bureau of Meteorology observations for the period 1961-2014), relative humidity and atmospheric pressure (see Box 4). This calculation, although relatively common, has historically been done by hand using specialised charts, for one or two values. An iterative function was developed in the R language to calculate wet bulb temperature from the climate model outputs.

Box 4 – Wet-bulb temperature calculations

Wet-bulb temperature was calculated using model output for dry-bulb temperature, relative humidity and atmospheric pressure, using the standard equations used by NOAA*:

1. Saturation Vapor Pressure (es):
   es = 6.112*10^((7.5*T)/(T+237.3)), where T = dry bulb temperature in C°
2. Actual Vapor Pressure, hPa (e):
   e = (es*RH)/100

3. Initial conditions for the iteration –
   Saturation Vapor Pressure at each increment:
   Ewg = 6.112*10^((7.5*Tw)/(Tw+237.3))

   Actual Vapor Pressure at each increment:
   eg = Ewg - ((P*(T - Tw))*0.00066*(1 +(0.00115*Tw)))
   where P = station pressure, Tw = wet bulb temperature at each increment
4. Vapour pressure difference (Ed):
   Ed = e-eg

These equations were solved iteratively, with wet bulb temperature being increased in increments of 10 degrees, and the increment being divided by 10 when consecutive Vapour pressure difference (Ed) changed sign. The iteration was stopped when Vapour pressure difference (Ed) was equal to 0 or the absolute value of Ed was less than 0.005.

Final Wet bulb temperature = wet bulb at final increment + (increment * previous sign)

* http://www.srh.noaa.gov/images/epz/wxcalc/wetBulbTdFromRh.pdf by Tim Brice and Todd Hall, National Oceanographic and Atmospheric Administration (NOAA)

4.2.3 Assessment of season length based on natural snow depth

Two independent datasets were used to assess how well snow over recent decades is represented in the regional climate model. Firstly, the modelled snow cover area (km^2) was compared with a daily snow cover dataset based on MODIS satellite data for the Australian alpine region for the period 2000–2010 at 500m resolution (Bormann et al. 2012). Secondly, modelled snow depth was compared with weekly observations of natural snow depth from the six Victorian alpine resorts, which were recorded from 1997-2014 for 18 weeks after the first Sunday in June. The results of these two comparisons are presented in Appendix B, Part II.

The model output was adjusted against observations provided by the ARCC at each resort from 1997-2014.

Snow depth from the model was compared to the target snow profile for each resort. The target snow profile describes the amount of snow required at particular times of year to ensure the successful long-term operation of each resort.

Table 4.2: Target snow depth (cm) profiles at the Victorian resorts

Resort	Target snow depth (cm)				
	1st June	30th June	31st July	31st August	30th Sept
Mt Hotham	1	30	60	100	40
Mt Buller	1	30	50	90	20
Falls Creek	1	30	60	100	40
Lake Mountain	1	30	30	30	10*

*Changed from value in Hennessey et al 2008 after consultation with resort staff.

**Mt Stirling is not shown because it does not have downhill runs or snowmaking (a cross-country skiing area). No profile was provided for Mt Baw Baw.

4.2.4 Snowmaking potential

As natural snowfall declines, the viability of snowmaking will be influenced by the frequency of wet bulb temperatures suitable for making snow.

The number of hours suitable for snowmaking based on three threshold temperatures (-2°C, -1°C, 0.5°C) are presented here. Firstly, we calculate the number of hours that accumulate before the start of the ski season (June 3rd), to assess the capacity of each resort to prepare for the season start. Secondly, the number of hours per week suitable for snowmaking over the year is presented, to provide an indication of season length based on the ability to make snow.

4.2.5 Scope of study

This report has focussed on the influence of natural snow cover decline and rising temperatures on future snowmaking conditions. However, there are many physical effects not considered in this report that will influence when and where snow can be made. These include the temperature of water used for snowmaking, the influence of aspect and topography on snow retention, warmer ground temperatures after summer, and increased melt rates.

The scarcity of reliable long-term observations across the Australian Alps region limits our ability to validate the model output against observations. The modelled data showed similar qualitative patterns in snow cover as calculated by previous authors using different methods (eg. Whetton et al. 1996, Bhend et al. 2012). Natural daily snow depth was available for 18 weeks in each year from 1997-2014, as the average depth from multiple plots (up to four) per resort. An adjustment was required to improve the fit of the model output with these observations (See Appendix B for validation of the modelled snow area and depth). At Mt Baw Baw, however, snow depths are significantly underestimated in these projections, even after the adjustment was applied, due to differences between the internal model topography and reality. It is reasonable to assume the direction of change is similar, although the magnitude of change is most likely overestimated, because this location is at a much lower elevation and experiences warmer temperatures in the model than would be expected in reality.

Given the difficulty in validating the model output, the primary emphasis of the conclusions is on temperature-based indices. The decline in snow is driven by future increases in temperature, so the conclusions are based on the variable with the most certainty in the projections (See Box 3, Figure 2). Temperature was bias-adjusted against gridded Bureau of Meteorology observations for the period 1961-2014 (Figure 4.3). This adjustment was then applied to future periods. Humidity could not be bias-adjusted, because there are no observations available for present decades.

The CFA results were produced using one downscaling technique, CCAM. The downscaling technique can introduce new biases in addition to those associated with the host model, so it is worthwhile to consider the projections in the context of the host models and other downscaling techniques (Ekström et al. 2015). Other projections for south-eastern Australia include NARCliM (Evans et al. 2014), which used the Weather Research and Forecasting (WRF) model, and the Bureau of Meteorology's statistical downscaling method BOM-SDM (Timbal and McAvaney 2001). The CMIP5 models projected a range in precipitation from more than -20% decreases to 15% increases. BOM-SDM consistently shows projections drier than host models in the Australian Alps region, and a larger decrease in precipitation than shown in the CCAM projections (>15% for most simulations). NARCliM found enhanced drying at high altitude compared to host models (CSIRO and Bureau of Meteorology 2015).

Given the topography and high natural variability in climate in the Australian Alps, the spatial and temporal resolution of the model remains a limitation. The mean values of a 5km grid cannot capture point localities exactly, particularly in the case of alpine resorts situated on mountain peaks. The use of three hourly data is a significant improvement on daily or monthly data, but estimates of hours accumulated below a wet bulb threshold are still likely to underestimate the actual number of hours, if, for example, the temperature drops below the threshold for periods shorter than three hours.

The results presented are from free-running climate models, so inter-annual, decadal and even multi-decadal variability during the 1960-2010 reference period will not be tied to observations. Changes over the next few decades are likely to be dominated by internal variability (which is included in the model, but not in-phase with observations) and the simulations can only be used to indicate general trends on ten year averages. For this reason we have presented the results for decadal time periods, not annual values for the coming decades. Nevertheless, the results show clearly that decadal averages of snow cover evolve in a highly systematic and progressive way.

Ultimately, how long skiing at the alpine resorts can remain viable will be determined by the economic and social costs of snowmaking. The economic costs of snowmaking will rise as natural snow cover declines, melting and evaporation rates increase and water and electricity costs rise. More snow will need to be made at warmer temperatures, particularly at the beginning of the ski season, and more likely at greater cost. Water supplies in the future may become less reliable, and competition for an increasingly scarce resource is likely to increase as downstream catchment areas become warmer and drier. The Australian Alps is an important catchment area for the Murray Darling River, Adelaide and many towns of South Australia. The value of the water flowing from the Victorian Alps catchments has been estimated as being at least $4 billion annually (based on 2005 water volumes), when all social and production benefits are considered (Worboys and Good 2011). In this context, the assumption of unlimited access to water in the future may be unsupported. Additionally, the six Victorian resorts are located on Crown Land that is annexed from, but in close proximity to, national parks in the alpine region. The consideration of impacts on conservation values will therefore continue to be important in the context of future water and energy use for snowmaking and grooming practices (Pickering et al. 2010).

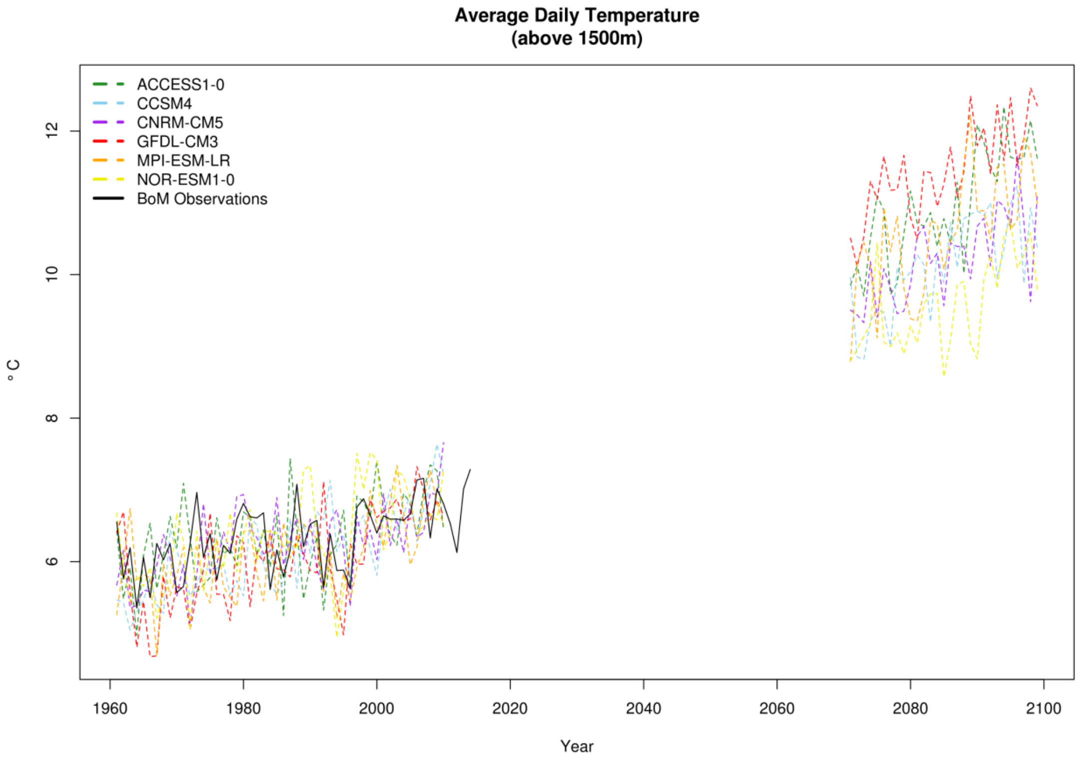


Figure 4.3: A comparison of average daily temperature above 1500m from Bureau of Meteorology observations and bias-adjusted model output. The coloured lines represent the six downscaled climate models, and the black line shows observations for the period 1961 to 2014.

4.3 Results

The shift between the current and future (end of century) time periods for each of the key variables is presented in Section 4.3.1. Section 4.3.2 provides more detail about the seasonal changes projected to occur at each resort between current and future time periods. Section 4.3.3 presents changes to ski season length and timing, based on natural snow. Finally, Section 4.3.4 considers changes to wet bulb temperature in the coming decades. All results are based on the high emissions scenario (RCP 8.5).

This section provides a general overview of results across all resorts. More detailed results are presented separately for each resort at the end of the report.

4.3.1 Changes projected at each resort between current and future time periods

Model output covering the current and future periods (1960-2010; 2070-2099) are presented in the separate resort sections (Figures 4.1A-F, and 4.2A-F). The frequency distribution shows the number of occurrences of a particular value, so can be used to highlight any shifts in the overall distribution, the mean or the variance (spread) of the values for each climate variable.

The results show that by the end of the century (2070-2099), under the high emissions scenario considered here:

1. There is an increase of approximately 4°C in mean temperature at all resorts and a shift towards higher temperatures across the distribution;
2. There is an increase in the number of extreme hot temperatures and a decrease in the number of very cold days at all resorts;
3. Mean wet bulb temperature does not increase as much as dry bulb temperature, due to the influence of humidity;
4. The shape of the distribution of temperatures (wet and dry bulb) does not change, with the exception of Falls Creek, where temperatures become more even (ie. lose the peak cold temperatures);
5. The coldest Winter temperatures increase by 2.5 to 7°C;
6. The hottest Summer days are approximately 5°C warmer in the future;
7. On average, Falls Creek is projected to experience the greatest decline in annual precipitation (-14%, model range -23% to 0%), followed by Lake Mountain (-13%, model range -20% to -3%), Mt Baw Baw (-11%, model range -19% to -2%) and Mt Hotham (-11%, model range -20% to +3%). Mt Stirling and Mt Buller are projected to have the lowest decline in precipitation (-7%, model range -13% to +6%);
   Values for three of the six resorts (Mt Hotham, Mt Buller and Mt Stirling) range from negative to positive, although the positive values represent very low percentages (3 to 6%). Mt Baw Baw and Lake Mountain show consistent declines in all models, and the range at Falls Creek is from decreases to no change in precipitation. Decreases in precipitation are consistent with recent declines in winter precipitation (Nicholls 2010), particularly in the western and high altitude regions (Chubb et al. 2011), and current understanding of the large scale drivers of the weather and climate in the Australian region. These include changes to blocking high pressure systems (Risbey et al. 2013), and poleward shifts in winter storm tracks (Frederiksen and Frederiksen 2007) and the subtropical ridge (Grose et al. 2015) that are expected to continue under ongoing climate change;
8. All models at all resorts project decreased Winter precipitation;
9. Snowfall declines substantially at all resorts, with mean annual snowfall decreasing from between 60% and 80%. Falls Creek shows the largest decline in snowfall (-79%), followed by

Mt Baw Baw (-78%), Mt Buller and Mt Stirling (-74%), Mt Hotham (-71%) and then Lake Mountain (-59%). This is due to a reduction in overall precipitation as well as a switch from snow to rain or sleet;

10. With warmer temperatures there is a reduction in the proportion of precipitation falling as snow. More snow falling as sleet has implications for the retention of snow;
11. Relative humidity is projected to decrease in the winter months, which may improve snowmaking opportunities at warmer temperatures;
12. Little change is projected to occur in wind speed or average wind direction at any resort.

There is close agreement between the climate models for temperature and wind variables, but a greater range in the projections of precipitation and snowfall (resort sections, Figures 4.5A-F, 4.6A-F). This degree of uncertainty is common in projections of rainfall (CSIRO and Bureau of Meteorology 2015), because the large-scale storm tracks in the projections are uncertain (Risbey and O'Kane 2011), and it is difficult to fully resolve the many physical processes involved in precipitation or the fine-scale spatial variability (Dowdy et al. 2015). However, all models show substantial reductions in snow cover, even those that project increasing precipitation by the end of the century (See Box 2 - Sources of uncertainty in projections of future climate). The range in values across the climate models is shown in Table 4.3.

4.3.2. Changes to monthly mean values between current and future time periods

Graphs of monthly values for each variable are presented to identify any changes in seasonality (resort sections, Figures 4.4A-F).

Increases in temperature are evident in every month of the year at all resorts. In the future, the monthly mean temperature of the winter months is projected to be more like that currently experienced in autumn and spring. Temperatures in June, July and August in the future are projected to be similar to those currently experienced in May or September. May and September in the future period show temperatures similar to those currently experienced in April or October. This may affect the ability for artificial snow to be laid down in the months leading up to the ski season.

The large range in monthly values for precipitation is due to the range in values across the six climate models (resort sections, Figures 4.4A-F). More detail is presented in Figures 4.5A-F. The six climate models give a range in the direction of change in precipitation in some months, with some models showing slight increases and others decreases. However, consistent with observations since the 1970's, all models project decreased precipitation to occur during the months April through to September. Substantial declines in monthly mean snowfall and snow depth is projected to occur by all models (resort sections, Figures 4.6A-F, 4.7A-F).

Table 4.3: Projected change in key climate variables at the Victorian alpine resorts between the current (1961-2010) and future (2070-2099) time periods. The multi-model mean is shown for each 30 year period, with the range of change between climate models shown in brackets.

		Temperature (°C)			Wet bulb temperature (°C)			Precipitation (mm)		Snowfall (mm)		Wind speed (m/s)	Wind direction (m/s)
		Minimum Winter	Maximum Summer	Mean annual	Minimum Winter	Maximum Summer	Mean annual	Mean Daily	Mean Annual	Maximum weekly	Mean Annual Maximum	Mean annual	
Mt Hotham	Current	-4.60 (-4.67, -4.49)	26.15 (25.56, 26.63)	7.81 (7.69, 7.95)	-17.70 (-20, -15.49)	20.60 (20.21, 21.48)	5.17 (5.09, 5.27)	5.75 (5.62, 5.96)	2098.75	12.88 (8.47, 16.26)	669.76	2.97 (2.95, 2.99)	234.00 (232.46, 235.40)
	Future	-1.43 (-1.84, -1.05)	31.51 (29.19, 33.42)	11.99 (10.94, 13.07)	-9.16 (-9.92, -7.89)	29.17 (25.01, 30)	8.68 (8.20, 9.26)	5.13 (4.50, 6.11)	1872.45	3.79 (1.17, 6.04)	197.08	2.95 (2.90, 3.00)	236.85 (234.18, 239.45)
	Change	3.17 (2.76, 3.60)	5.36 (3.16 , 7.45)	4.18 (3.17, 5.38)	8.54 (5.93, 12.11)	8.56 (4.79, 9.75)	3.51 (3.06, 4.13)	-0.62 (-1.46, 0.49)	-11% (-20%, +3%)	-9.09 (-13.33, -2.43)	-71% (-86%,-63%)	-0.02 (-0.06, 0.03)	2.85 (0.57, 4.90)
Mt Buller	Current	-3.83 (-3.96, -3.70)	27.06 (26.50 , 27.59)	8.57 (8.43 , 8.69)	-14.19 (-17.86, -11.62)	21.26 (20.63, 21.62)	5.66 (5.58, 5.78)	3.66 (3.60, 3.72)	1335.9	8.39 (6.78, 9.93)	436.28	3.03 (3.01, 3.05)	232.59 (231.20, 234.36)
	Future	-0.98 (-1.46, -0.51)	32.22 (30.12 , 34.11)	12.74 (11.65, 13.81)	-9.32 (-10.71, -8.27)	30 (30, 30)	9.10 (8.62, 9.66)	3.39 (3.14, 3.93)	1237.35	2.19 (0.94, 3.28)	113.88	3.03 (2.96, 3.10)	231.79 (227.92, 234.95)
	Change	2.85 (2.34, 3.44)	5.15 (3.13 , 7.27)	4.17 (3.10, 5.38)	4.87 (2.64, 8.86)	8.74 (8.38, 9.37)	3.44 (2.98, 4.06)	-0.27 (-0.58, 0.33)	-7% (-13%, +6%)	-6.20 (-7.87, -4.15)	-74% (-86%,-70%)	0 (-0.07, 0.05)	-0.81 (-5.57, 3.42)
Falls Creek	Current	-9.54 (-10.08, -9.14)	22.44 (21.85 , 23.07)	5.60 (5.51 , 5.73)	-22.92 (-30, -20.03)	20 (20, 20)	3.34 (3.24, 3.46)	8.10 (7.85, 8.48)	2956.5	29.04 (24.09, 32.39)	1510.08	4.44 (4.40, 4.47)	250.15 (249.08, 250.98)
	Future	-2.33 (-2.96, -1.91)	27.79 (25.37 , 29.73)	10.07 (9.02 , 11.19)	-11.78 (-13.43, -9.85)	24.71 (21.44, 30)	7.17 (6.67, 7.80)	7.00 (6.04, 8.50)	2555	6.04 (3.58, 9.20)	314.08	4.39 (4.30, 4.48)	254.27 (251.12, 257.47)

	Change	7.21 (6.64 , 7.98)	5.35 (3.11 , 7.44)	4.47 (3.50, 5.65)	11.14 (8.16, 16.57)	4.71 (1.44, 10)	3.83 (3.39, 4.46)	-1.10 (-2.43, 0.65)	-14% (-23%, 0%)	-23.00 (-28.81, -15.38)	-79% (-85%,-72%)	-0.05 (-0.14, 0.02)	4.12 (1.78, 7.13)
Mt Baw Baw	Current	-1.47 (-1.73, -1.34)	-2.88 (-3.06, -2.79)	9.23 (9.08, 9.42)	-9.60 (-12.18, -7.03)	21.49 (20.58, 22.26)	6.34 (6.25, 6.49)	5.00 (4.89, 5.09)	1825	6.08 (5.57, 7.10)	316.16	3.23 (3.21, 3.27)	173.87 (172.38, 176.37)
	Future	1.10 (0.64 , 1.71)	-0.52 (-0.88, 0.00)	13.12 (12.21, 13.97)	-5.45 (-6.33, -4.31)	29.00 (24.03, 30)	9.61 (9.15, 10.05)	4.45 (3.95, 5.00)	1624.25	1.37 (1.05, 1.67)	71.24	3.25 (3.22, 3.29)	173.32 (169.81, 177.46)
	Change	2.57 (2.09, 3.43)	2.36 (1.98, 3.06)	3.89 (2.99, 4.89)	4.14 (2.02, 6.58)	7.51 (2.64, 9.42)	3.27 (2.81, 3.77)	-0.54 (-1.14, -0.01)	-11% (-19%, -2%)	-4.71 (-5.99, -4.21)	-78% (-81%,-76%)	0.02 (-0.03, 0.07)	-0.55 (-4.63, 3.97)
Lake Mountain	Current	-2.88 (-3.14, -2.76)	26.38 (25.87, 27.02)	8.35 (8.20, 8.52)	-12.56 (-14.90, -11.42)	21.46 (21.05, 22.23)	5.76 (5.68, 5.90)	4.03 (3.93, 4.15)	1470.95	13.45 (10.97, 15.28)	699.4	3.37 (3.34, 3.39)	248.75 (247.67, 249.55)
	Future	-0.17 (-0.61, 0.36)	31.58 (29.55, 33.41)	12.39 (11.40, 13.34)	-7.90 (-8.71, -7.38)	30 (30, 30)	9.14 (8.68, 9.63)	3.52 (3.13, 4.02)	1284.8	5.45 (3.35, 9.91)	283.4	3.36 (3.28, 3.44)	250.01 (248.07, 252.21)
	Change	2.72 (2.26, 3.51)	5.20 (3.20, 7.41)	4.04 (3.06, 5.14)	4.65 (3.41, 6.19)	8.54 (7.77, 8.95)	3.38 (2.93, 3.93)	-0.51 (-1.01, 0.04)	-13% (-20%, -3%)	-8.00 (-10.26, -5.38)	-59% (-69%,-35%)	-0.01 (-0.08, 0.05)	1.26 (-1.41, 3.82)
Mt Stirling	Current	-3.83 (-3.96, -3.70)	27.06 (26.50, 27.59)	8.57 (8.43 , 8.69)	-14.19 (-17.86, -11.62)	21.26 (20.63, 21.62)	5.66 (5.58, 5.78)	3.66 (3.60, 3.72)	1335.9	8.39 (6.78, 9.93)	436.28	3.03 (3.01, 3.05)	232.59 (231.20, 234.36)
	Future	-0.98 (-1.46, -0.51)	32.22 (30.12, 34.11)	12.74 (11.65, 13.81)	-9.32 (-10.71, -8.27)	30 (30, 30)	9.10 (8.62, 9.66)	3.39 (3.14, 3.93)	1237.35	2.19 (0.94, 3.28)	113.88	3.03 (2.96, 3.10)	231.79 (227.92, 234.95)
	Change	2.85 (2.34, 3.44)	5.15 (3.13, 7.27)	4.17 (3.10, 5.38)	4.87 (2.64, 8.86)	8.74 (8.38, 9.37)	3.44 (2.98, 4.06)	-0.27 (-0.58, 0.33)	-7% (-13%, +6%)	-6.20 (-7.87, -4.15)	-74% (-86%,-67%)	0 (-0.07, 0.05)	-0.81 (-5.57, 3.42)

4.3.3 Shifts in the timing and duration of the ski season based on natural snow

The Victorian ski season at the higher elevation resorts traditionally extends from early June to early October. This period is shorter at the lower elevation resorts which have less reliable snowfall and shorter ski seasons. The minimum snow depth required for downhill skiing is generally considered to be 30cm (Hennessy et al. 2008), and a minimum of 60-70 days of operation is considered necessary for a viable season (Pickering 2011).

The change in the duration and timing of the ski season between current and future periods based on natural snow depth is shown in the resort sections, Figures 4.8A-F. The target profiles (Table 4.2) are not reached with natural snow over recent decades in the simulations.

From the 1960's to 2010, the models show a steady reduction in snow depth, and the duration of the ski season has contracted, with a later start and earlier finish. This is consistent with observations over this period (Bhend et al. 2012). Assuming a depth of 30cm is required for skiing, the season length has contracted by 17% to 28% across the resorts over recent decades, and is projected to contract by 65% to 90% by the 2070 period relative to 2000-2010. Projections show the greatest contraction in season length at Mt Stirling and Mt Buller, and the lowest contraction at Mt Baw Baw and Falls Creek.

These results are in line with previous research, which has documented substantial declines in season length over the period 2000–2010 (Bormann et al. 2012). While recent declines have been attributed to earlier seasonal snowmelt, the projections suggest that later season onset is also likely to occur under future conditions. Hennessy et al. (2008) suggested that by 2020 the average ski season length could be reduced by 10 to 60% at lower altitude resorts and 5 to 30% at sites above 1600m. By 2050, their study projected contractions in ski season length by 15-99%. The new projections provide confirmation that season length will contract at all resorts, and suggest that the contraction by 2070 may be at the higher range of previous estimates.

4.3.4 Changes to the frequency of suitable snowmaking conditions under future climate conditions

The extended time series of 3 hourly wet bulb temperature, based on the six climate models (1960-2010, 2070-2099) and the statistical method (2011-2069) are shown for each resort in Appendix C.

The number of hours suitable for snowmaking (below -2°C) that accumulate by the season start (June 3rd) at the resorts over time is shown in Figure 4.4. Figures for all thresholds are presented in the separate resort sections (resorts sections, Figures 4.9A-F to 4.11A-F). The results show a gradual decline from 1960 to 2000, followed by a marked drop in available hours for snowmaking between the 2020's and 2030's. Opportunities for snowmaking relative to the 2010's are halved by 2030-2040 at all resorts, with the exception of Falls Creek where opportunities halve by 2040-2050.

If warmer thresholds are accepted, with the associated trade-offs in cost and quality of snow, the number of hours suitable for making snow is higher than at colder temperatures.

The accumulation of hours below different threshold temperatures can be used to indicate the start of the ski season, and the quality of snow that may be made (Figures 4.9C to 4.11C). Even if snow were made in all suitable hours, the ski season is projected to start later in the year at all resorts. The changes equate to a relative shift in the start of the ski season from early June in the 1960's, to the end of June in the 2020's, and early to late July by the 2030's and 2040's. At Mt Baw Baw, the season start date based on accumulated snowmaking hours shifts to after the end of the current season (10th October) by the 2050's. This point is reached by the end of the century at Falls Creek, Mt Buller and Mt Stirling and Mt Hotham. At Lake Mountain, by the end of the century, the same number of accumulated snowmaking hours as were available in the 1960's is not reached at any time of the year.

These calculations of snowmaking potential are independent of natural snowfall. It is likely that some natural snowfall would be required to form a base on which artificial snow would be laid down. The timing of natural snowfall leading up to the ski season may, therefore, limit snowmaking potential in the future, particularly as the ground temperature is likely to be warmer following warmer summer months under ongoing climate change.

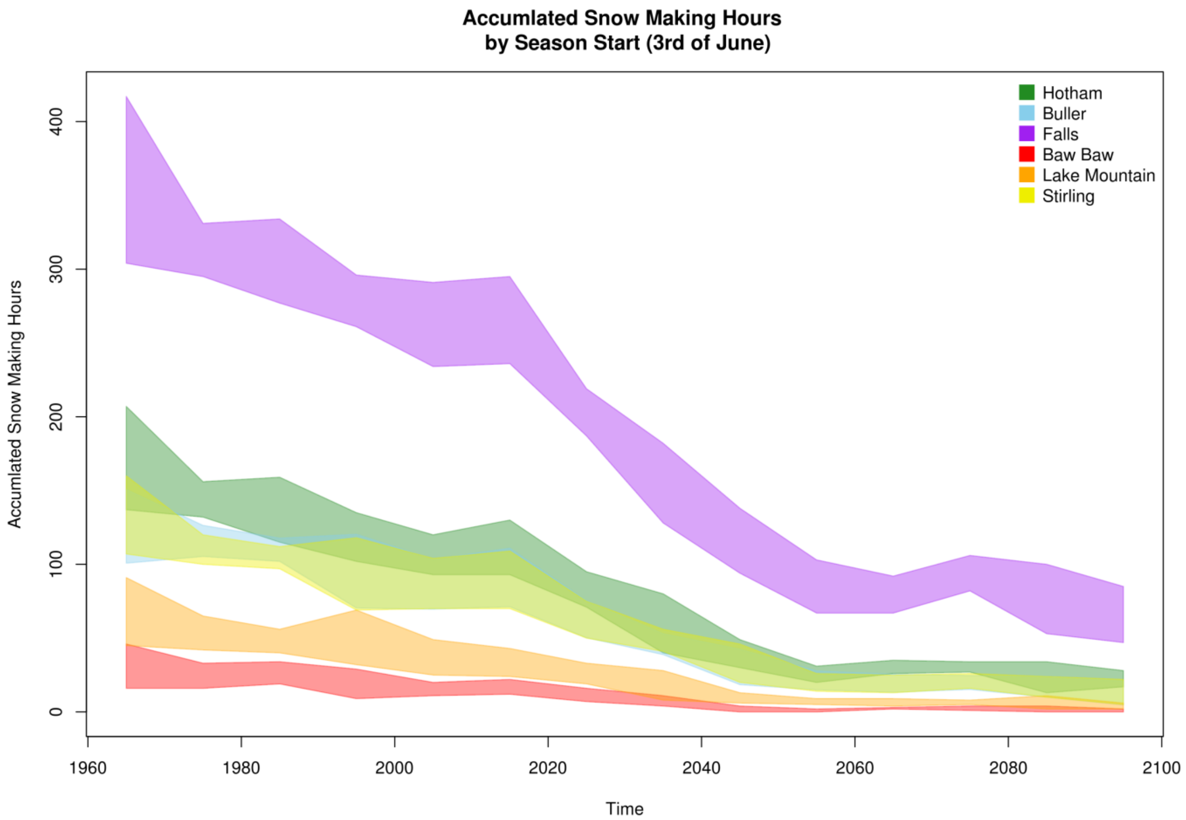


Figure 4.4: Number of hours suitable for snowmaking (below -2°C) accumulated by season start date (June 3rd) at the Victorian alpine resorts over time. The range in each envelope represents inter-annual variability and the range across the six climate models.

4.4 Conclusion

The Victorian alpine resorts are projected to be 4-5°C warmer, with 5-20% less precipitation and 60-80% lower annual snowfall under a high emissions scenario by late in the century (relative to 1961-1990). While natural inter-annual variability in snowfall in the Australian Alps may dominate over the next decade, by the end of the century, the trend is clear. Substantial reductions in natural snowfall are projected at all resorts by all models, resulting in later ski season start and earlier season finish.

As the climate continues to change, the viability of skiing at the alpine resorts will rest on the ability to make snow. However, in the future, more snow will need to be made at warmer temperatures, and therefore at greater cost, particularly at the beginning of the ski season. Opportunities for snowmaking are projected to decline substantially in the next two decades, although trade-offs in cost and snow quality may extend snowmaking opportunities.

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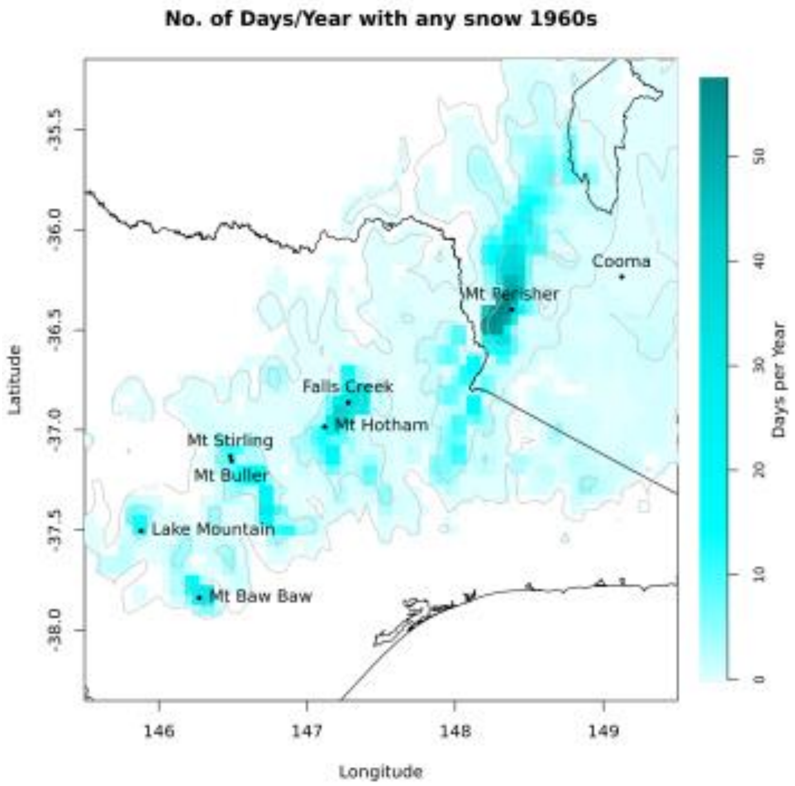
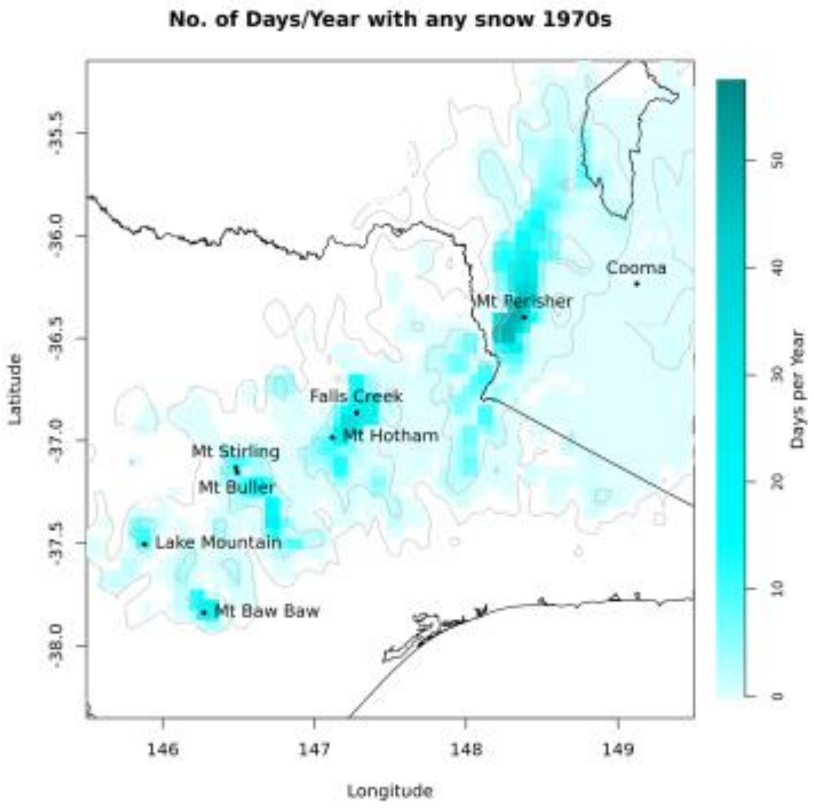
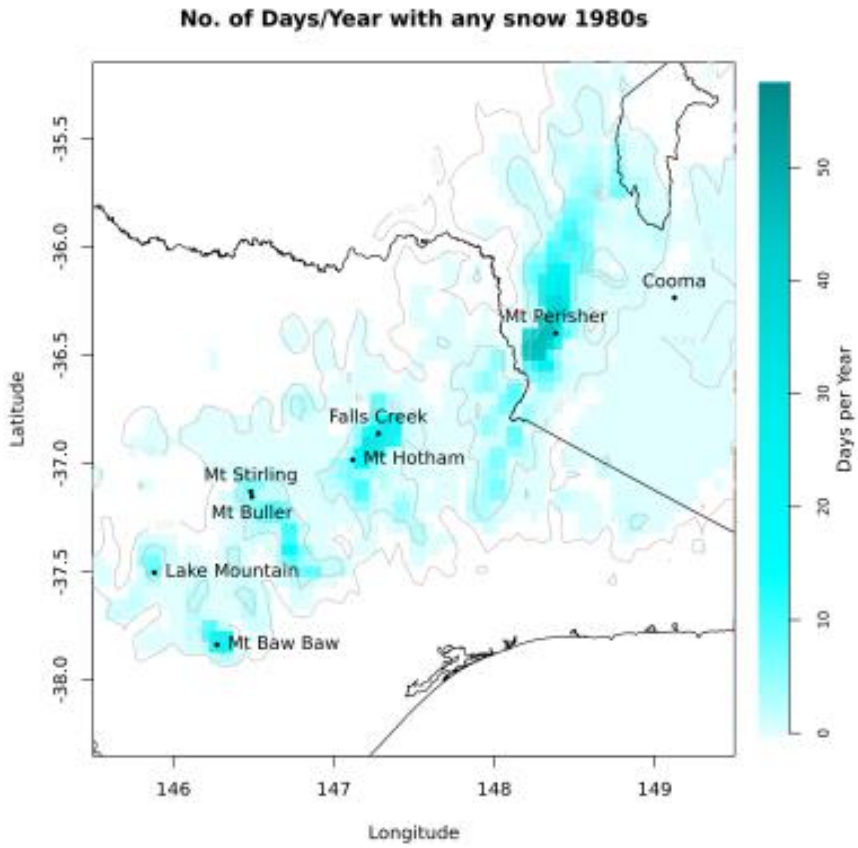
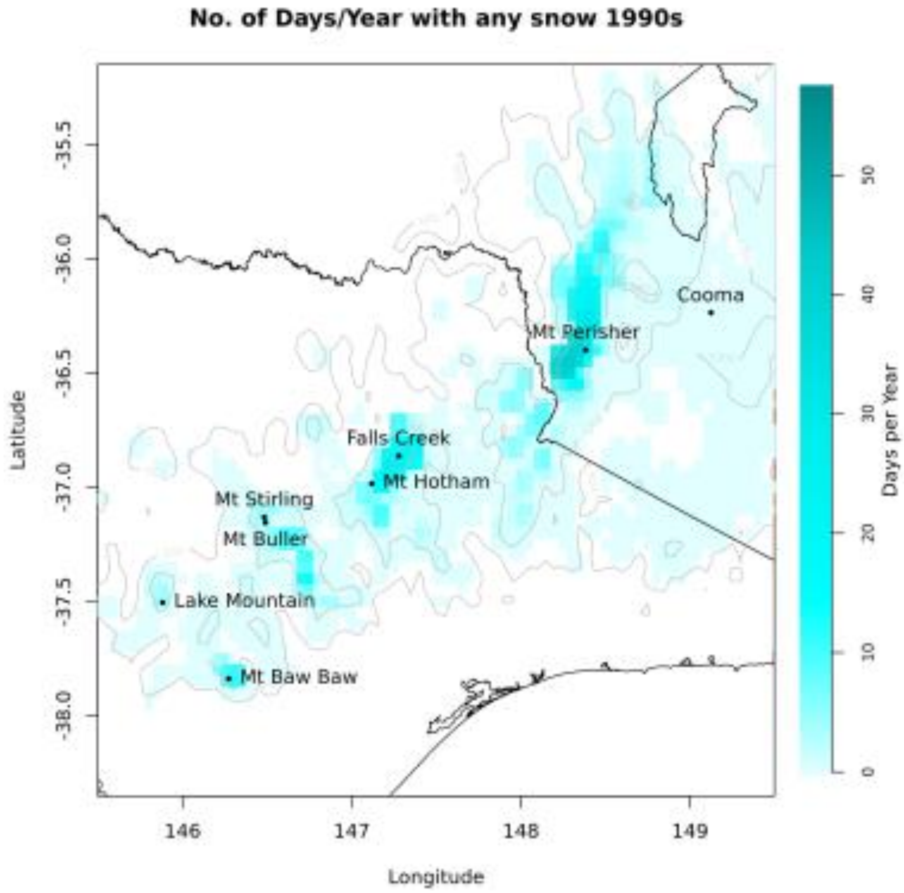
Appendix A, Part II

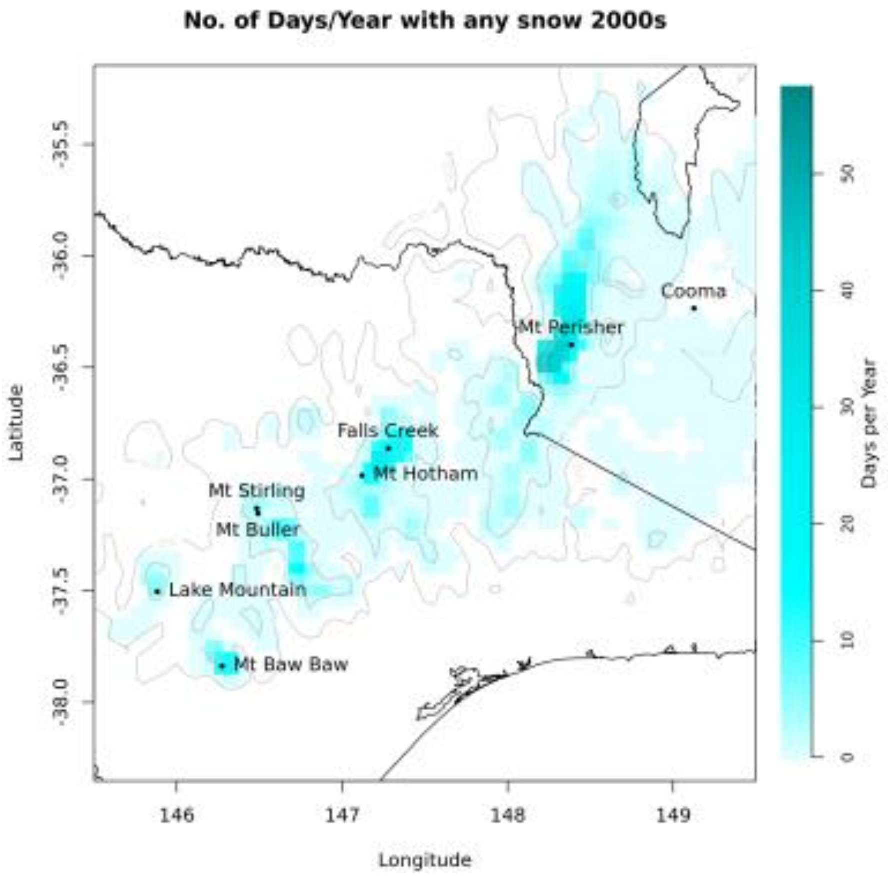
Maximum extent of snow projected over the Australian Alps for past and future time periods, shown as all grid cells with any snow at all in each decade from any of the six climate models.

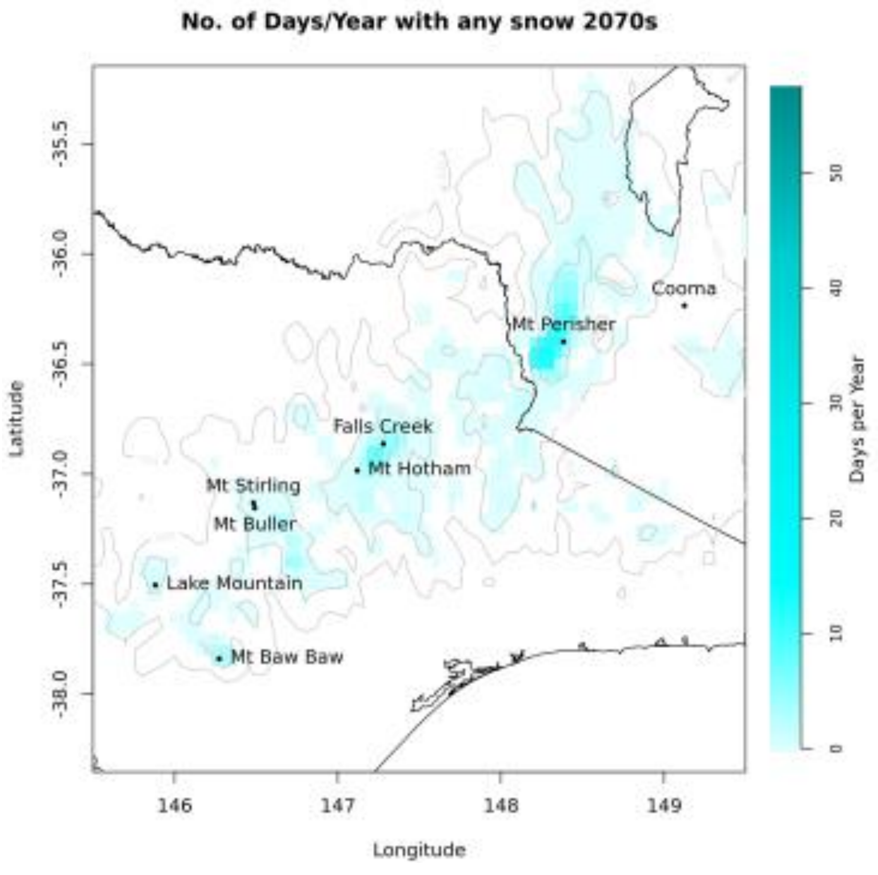


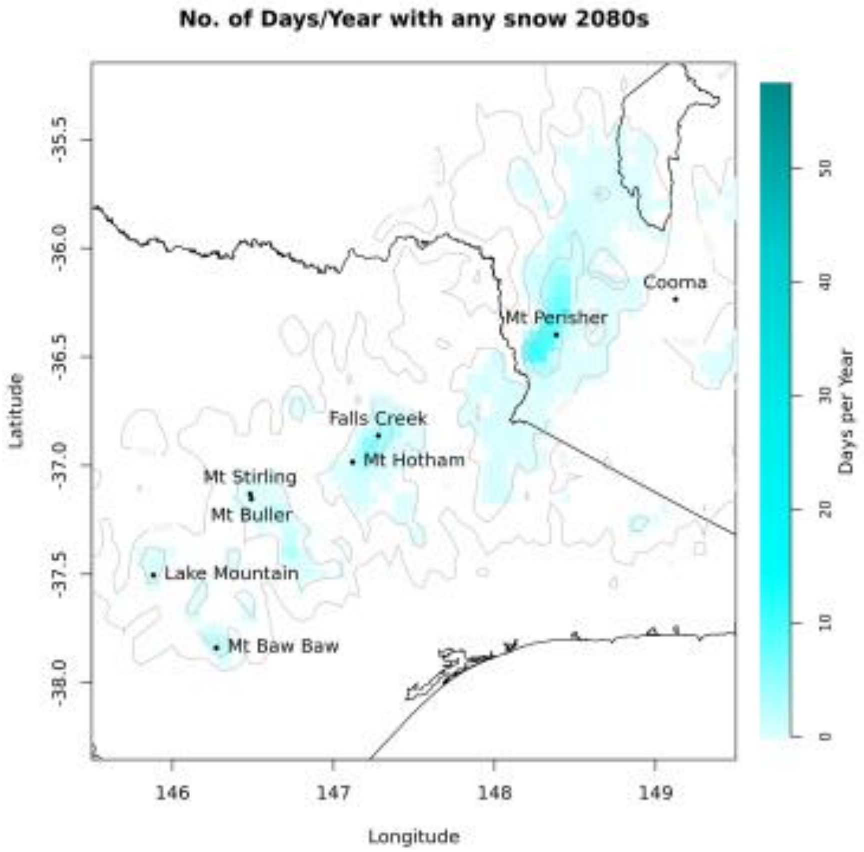


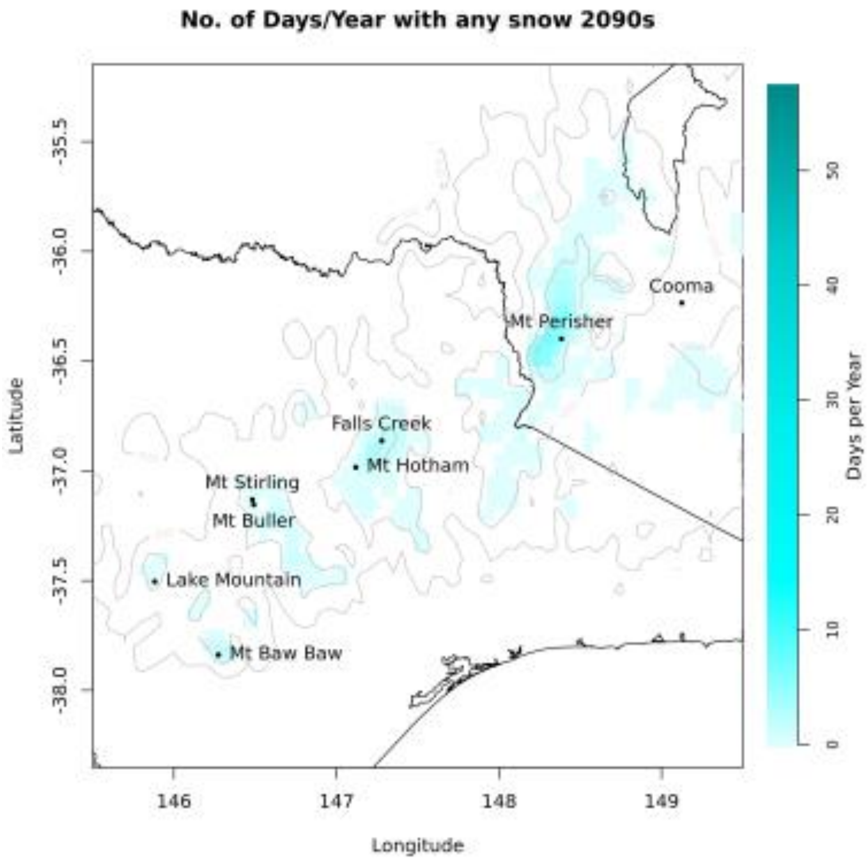

No. of Days/Year with any snow 1980s
Cooma
Mt Perisher
Falls Creek
Mt Hotham
Mt Stirling
Mt Buller
Lake Mountain
Mt Baw Baw
Latitude
-35.5
-36.0
-36.5
-37.0
-37.5
-38.0
Longitude
146
147
148
149
Days per Year
0
10
20
30
40
50


No. of Days/Year with any snow 1990s
Cooma
Mt Perisher
Falls Creek
Mt Hotham
Mt Stirling
Mt Buller
Lake Mountain
Mt Baw Baw
Latitude
-35.5
-36.0
-36.5
-37.0
-37.5
-38.0
Longitude
146
147
148
149
Days per Year
0
10
20
30
40
50


No. of Days/Year with any snow 2000s
Latitude
Longitude
Days per Year
Cooma
Mt Perisher
Falls Creek
Mt Hotham
Mt Stirling
Mt Buller
Lake Mountain
Mt Baw Baw
-35.5
-36.0
-36.5
-37.0
-37.5
-38.0
146
147
148
149
0
10
20
30
40
50


No. of Days/Year with any snow 2070s
Latitude
Longitude
Days per Year
Cooma
Mt Perisher
Falls Creek
Mt Hotham
Mt Stirling
Mt Buller
Lake Mountain
Mt Baw Baw
-35.5
-36.0
-36.5
-37.0
-37.5
-38.0
146
147
148
149
0
10
20
30
40
50


No. of Days/Year with any snow 2080s
Latitude
Longitude
Days per Year
-35.5
-36.0
-36.5
-37.0
-37.5
-38.0
146
147
148
149
0
10
20
30
40
50
Cooma
Mt Perisher
Falls Creek
Mt Hotham
Mt Stirling
Mt Buller
Lake Mountain
Mt Baw Baw


No. of Days/Year with any snow 2090s
Latitude
Longitude
Days per Year
-35.5
-36.0
-36.5
-37.0
-37.5
-38.0
146
147
148
149
0
10
20
30
40
50
Cooma
Mt Perisher
Falls Creek
Mt Hotham
Mt Stirling
Mt Buller
Lake Mountain
Mt Baw Baw

Appendix B, Part II

Validation of modelled snow area and depth

Two independent datasets were used to assess how well snow over recent decades is represented in the regional climate model. Firstly, the modelled snow cover area (km^2) was compared with a daily snow cover dataset based on MODIS satellite data for the Australian alpine region for the period 2000–2010 at 500m resolution (Bormann et al. 2012). Secondly, modelled snow depth was compared with weekly observations of natural snow depth from the six Victorian alpine resorts, which were recorded from 1997-2014 for 18 weeks after the first Sunday in June.

Snow cover

The modelled data show similar qualitative patterns in snow cover as calculated by previous authors using different methods (eg. Whetton et al. 1996, Bhend et al. 2012). The climate model simulates a greater extent of snow cover across the region compared to the satellite data (Figure B.1a, b). The satellite data are known to systematically underestimate snow cover, particularly in areas of marginal snow (Bormann et al. 2012), for two reasons. Firstly, because the data used is a binary product, only pixels with at least 50% of the area reporting a snow signal are counted as snow covered. Secondly, difficulties in distinguishing between cloud and snow substantially reduce the numbers of usable observations. After cloud obscured images were excluded, the snow cover extent map (Figure B.1b) was based on 358 observations, which is only an average of 1–2 clear-sky images per week during each snow season.

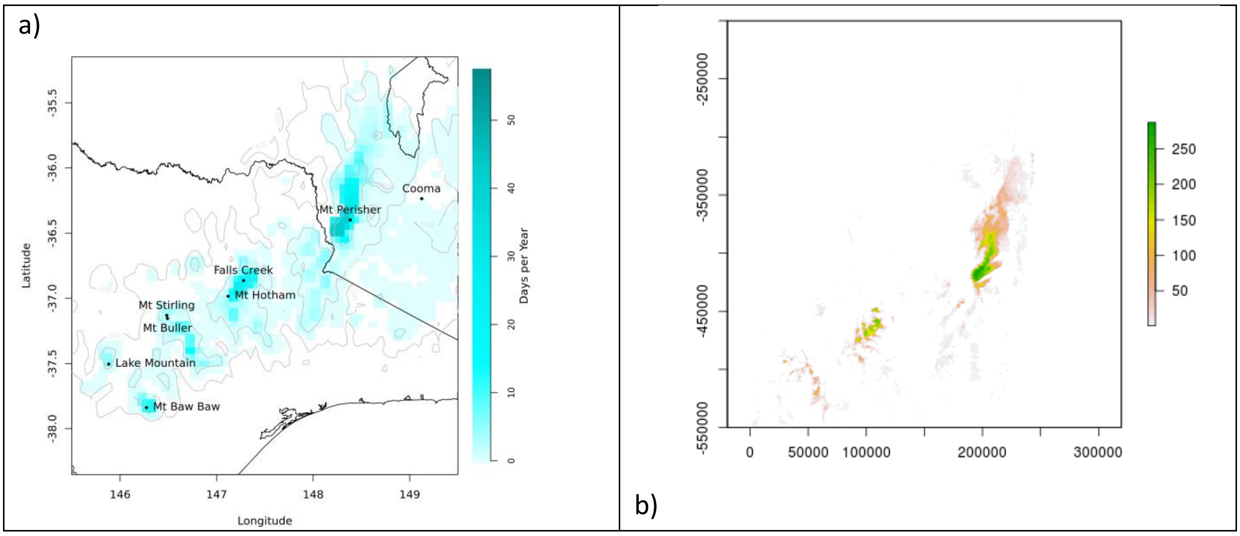


Figure B.1: A comparison of maximum snow extent for the period 2000–2010 from a) the regional climate model (~5km resolution) and b) MODIS satellite data (500m resolution, MADI threshold > 6) from (data from Bormann et al. 2012).

Snow depth

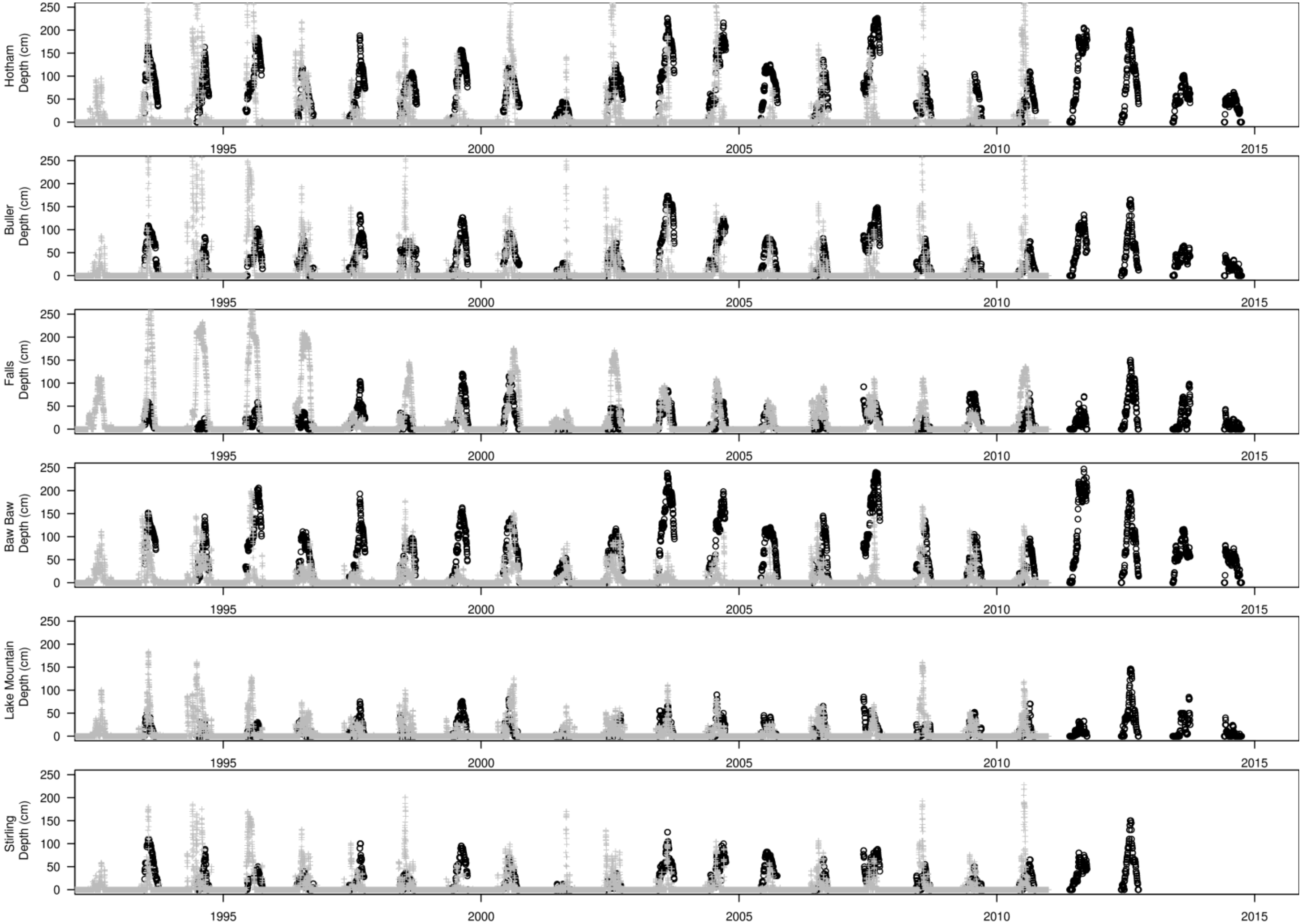
Comparing point locations with the mean of a 5km grid from the climate model makes validation difficult, particularly when we are attempting to compare to resorts located on mountain peaks. Observations of snow depth are scarce across the Alps region, particularly at high elevations. In addition, snow depth recorded by the resorts includes artificial and natural snow. Since each climate model is free-running (ie. not tied to observations), the inter-annual variability within each is not synchronised. In this case, the multi-model mean better represents the observations, because averaging the six models smooths out the inter-annual and decadal components of natural variability.

The model output was adjusted to more closely match the observations of snow depth at each resort. After adjustment, the multi-model mean snow depth reproduces the observed yearly snow depth profile well, although the models tend to overestimate snow depth. Mt Baw Baw is the exception to this, with snow depth generally underestimated by the models. A temporal adjustment was also applied, because all models projected the ski season starting earlier than it does in reality. This is most likely because they follow the solar cycle and do not adequately represent the 'atmospheric lag' where the coldest days are in August/September, rather than June/July. This effect was adjusted by adding 20 days to the time to shift the season in line with the observations. These adjustments were then applied to all model output from other years.

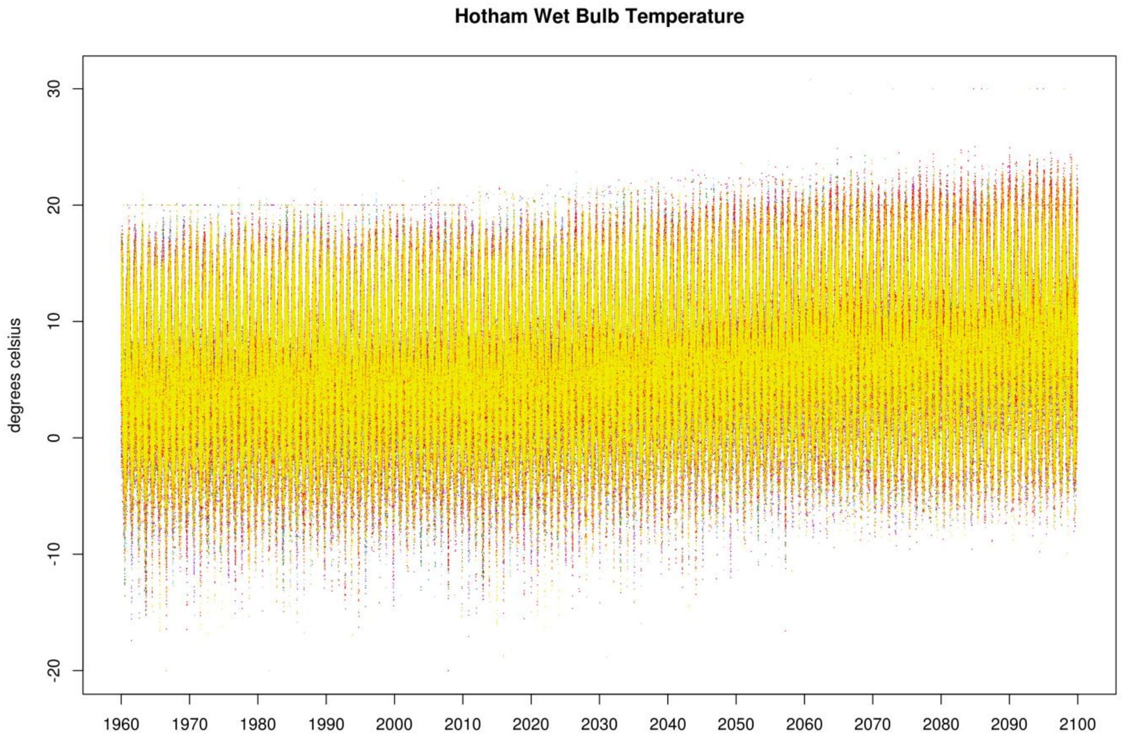
The comparison between the adjusted multi-model mean snow depth at each resort and observations from the period 1997-2014 is shown in Figure B.2.

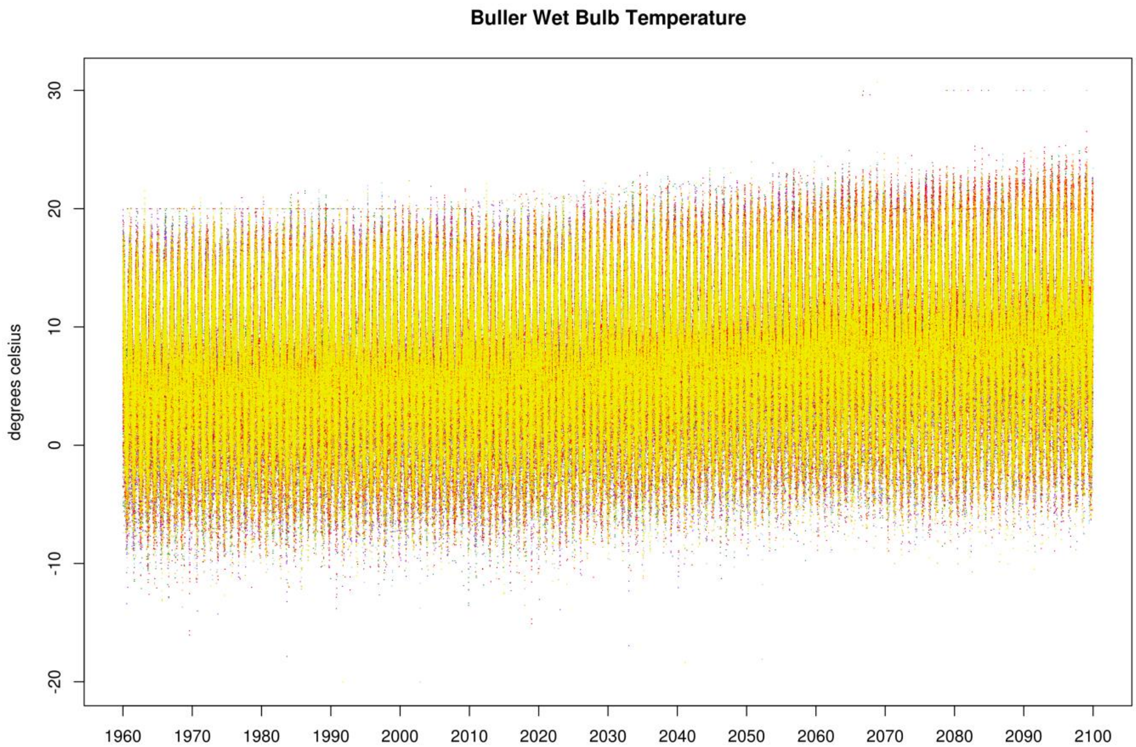
An assessment of the Crocus snow model (Vionnet et al. 2012) was carried out to investigate whether the output from the regional climate model could be improved by simulating the development of snow cover as a function of the radiative balance, turbulent heat and moisture fluxes between the snow pack and the atmosphere. This model has been run operationally for avalanche forecasting in France for more than two decades, but has not been applied to Australian conditions. However, further validation was found to be necessary under Australian conditions, where soil conditions have more effect on snow properties because the snowpack is shallower and more ephemeral (Lafaysse et al. 2013).

Figure B.2: A comparison of adjusted 3 hourly snow depth with observations from the six Victorian alpine resorts. Black circles represent observations, grey represent adjusted model output.

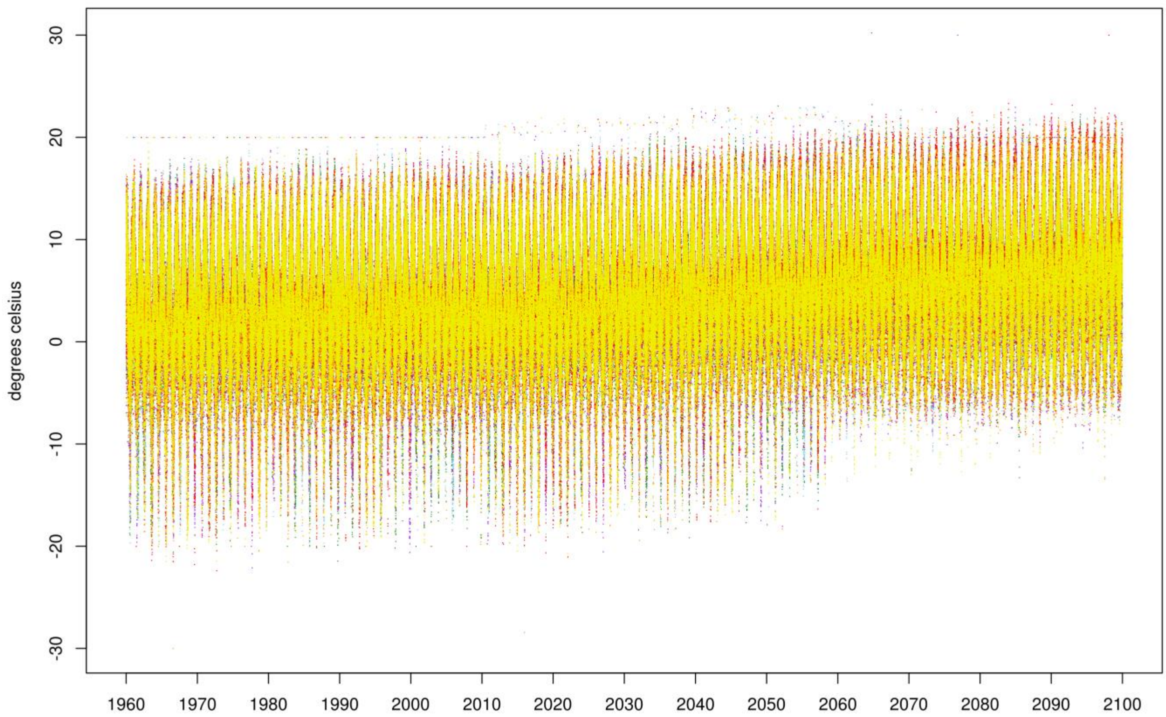


Appendix C, Part II
Wet bulb temperatures at 3 hourly periods, from 1961-2100, at the Victorian alpine resorts. Values for the decades 1960-2010 and 2070-2090 are based on the multi-model mean of 3 hourly data, while the decades 2020-2060 are statistically derived.

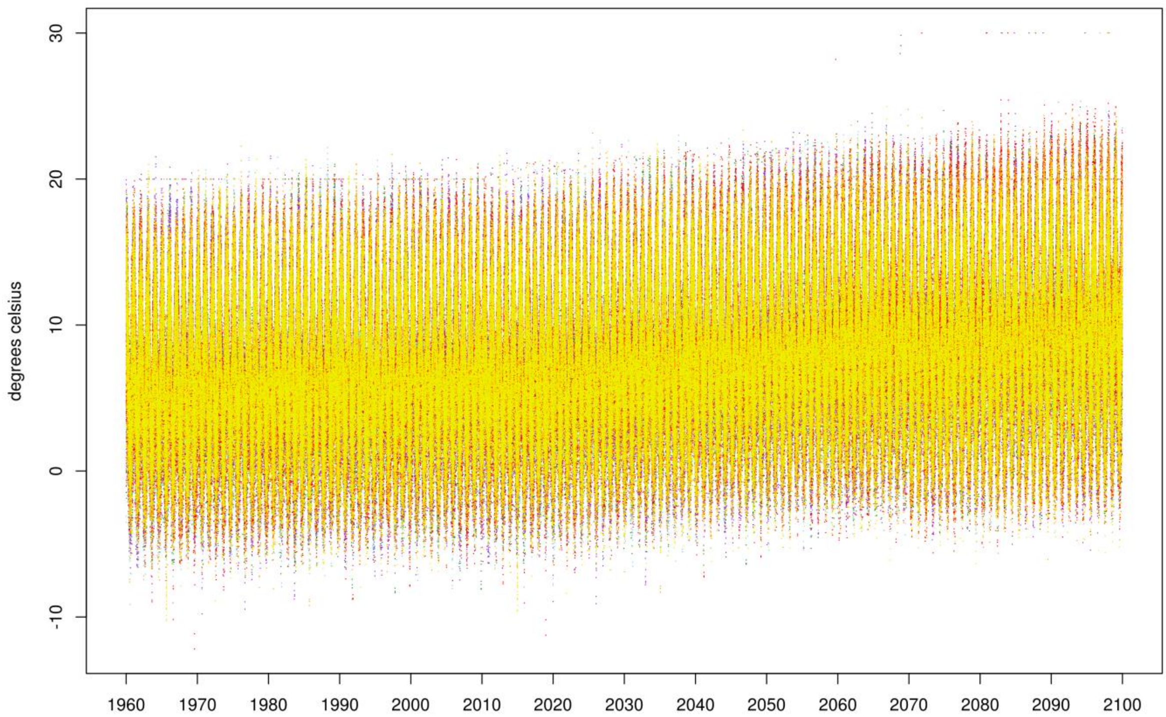


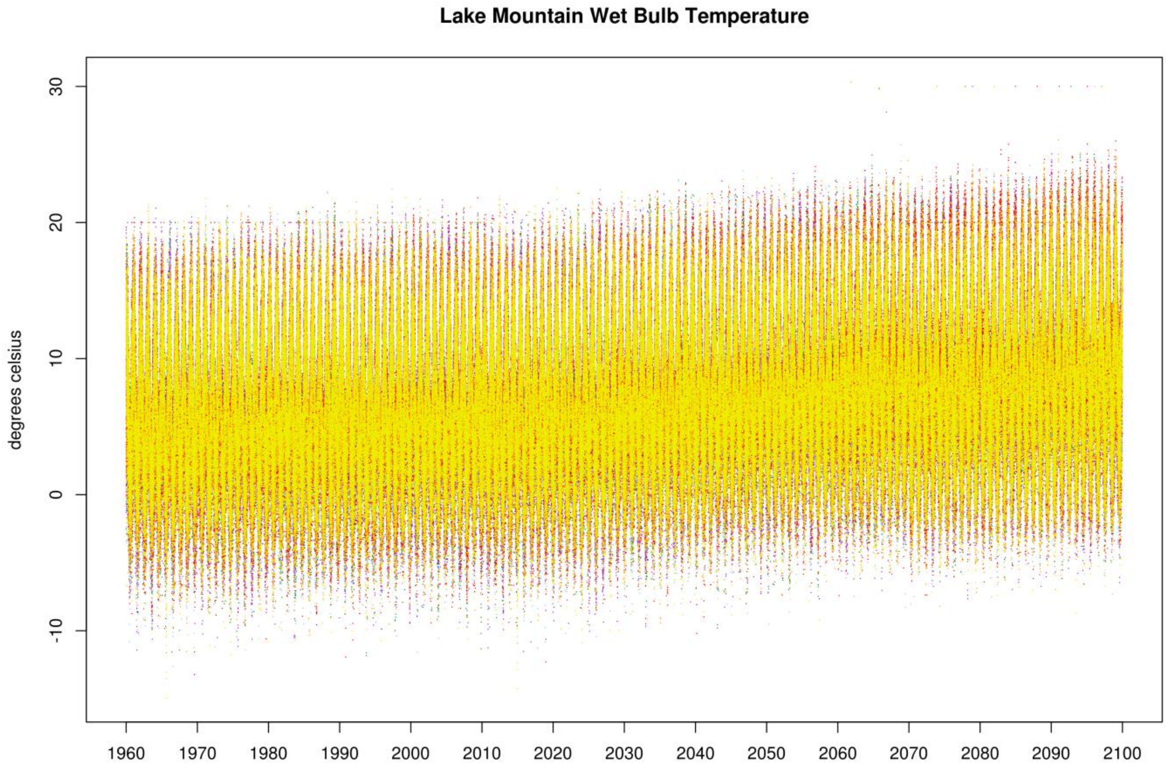


Falls Wet Bulb Temperature

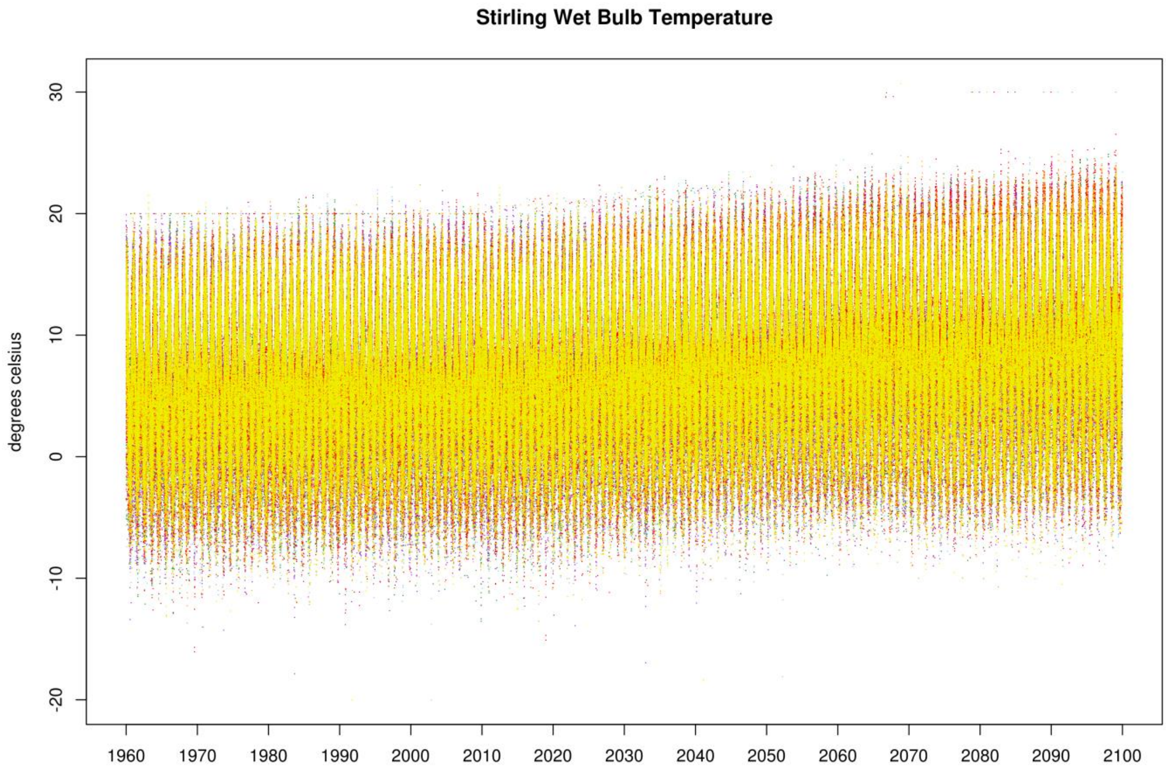


Baw Baw Wet Bulb Temperature





Lake Mountain Wet Bulb Temperature
degrees celsius
30
20
10
0
-10
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100



Stirling Wet Bulb Temperature
degrees celsius
30
20
10
0
-10
-20
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100

A. MT HOTHAM (elevation 1860m)

This section describes the changes in climate that are projected to occur at the Mt Hotham resort. An explanation of the Climate Futures for the Australian Alps projections, the methods used and results from across all of the Victorian Alpine resorts can be found in the main report. The main report also provides important information about the scope of the study and considers the uncertainty associated with projections of future climate.

Relative to recent decades (1961-2010), the projections for Mt Hotham by the end of the century, under a high emissions scenario, show:

1. An increase in mean annual temperature of 3-5°C (mean of 4°C);
2. An increase in the number of extreme hot temperatures and a decrease in the number of very cold days;
3. The temperature of the coldest days in winter increases by approximately 3°C, while the temperature of the hottest summer days increase by approximately 5°C;
4. A mean decrease in annual precipitation of 11%. However, a maximum decrease of 20% to a slight increase of +3% is shown across the six climate models;
5. A decrease in precipitation from May through to October for all climate models;
6. Substantial reductions in snowfall, from 86% to 63% less snowfall than the baseline period (mean reduction of 70%);
7. With warmer temperatures there is a reduction in the proportion of precipitation falling as snow. More snow falling as sleet has implications for the retention of snow;
8. No change in wind speed or wind direction.

A1 Changes between current and future periods

The changes projected to occur at Mt Hotham between the current (1961-2010) and future (2070-2099) time periods are shown in Table 4.1A.

Figure 4.1A shows the frequency distribution for key climate variables in the modelled current (1961-2010) and future (2069-2099) time periods. The number of occurrences of a particular value is used to highlight any shifts in the overall distribution, the mean or the variance (spread) of the values for each climate variable. The shape of the distribution of temperatures (wet and dry bulb) does not change, but there is a shift towards higher temperatures across the distribution. There is an increase in the number of extreme hot temperatures and a decrease in the number of very cold days.

The daily values across all models are shown in Figure 4.2A.

The proportion of precipitation falling as snow in the historical, current and future periods are shown in Figure 4.3A. Fewer snow days in the future means that there will be fewer days when precipitation is 100% snow. There is also a reduction in the proportion of snow, with more snow falling as sleet. This has implications for the retention of natural or artificial snow.

A2 Changes to monthly mean values

A comparison of the multi-model mean monthly values of key climate variables in the current and future time periods is presented in Figure 4.4A. Increases in temperature are evident in every month of the year. In the future, the monthly mean temperature of the winter months, (June, July and August) is projected to be more like that currently experienced in autumn and spring. Temperatures in June, July and August in the future are projected to be similar to those currently experienced in May or September. May and September in the future period show temperatures similar to those currently experienced in April or October. This could potentially affect the ability for artificial snow to be laid down in the months leading up to the ski season.

Similarly, mean monthly wet bulb temperatures increase in all months, and show the same shifts in winter towards temperatures currently more typical of autumn and spring. Wet bulb temperature does not increase as much as dry bulb temperature, however, because wet bulb temperature reflects the influence of humidity. Note that this summary of monthly values does not show the very low temperatures because it is based on daily means. More detailed analyses of the number of hours per day suitable for snowmaking at particular threshold temperatures are provided in Section A4.

There are no changes to wind speed or direction in any month of the year. Projections of humidity, however, which showed no change in annual means, is projected to decrease slightly in April, May and August, with more substantial reductions evident in September, October and November (Figure 4.4A).

The large range in monthly values for precipitation is due to the range in values across the six climate models (Table 4.1A). However, all models project decreased precipitation to occur during the months May through to October (Figure 4.5A). In the other months, there is more inconsistency in the direction of change, with some models showing slight increases and others decreases. Substantial reductions in snowfall and snow depth are projected by all climate models in all months (Figure 4.6A, Figure 4.7A). Not only are there fewer days when it snows, but there is reduced snowfall on days when it does snow.

A3 Shifts in the timing and duration of the ski season based on natural snow

The change in the duration and timing of the ski season between current and future periods based on natural snow depth is shown in Figure 4.8A.

All models agrees with observational records that indicate a steady reduction in snow depth over recent decades, from the 1960’s to 2010’s, and the duration of the ski season has contracted, with a later start and earlier finish. Assuming a depth of 30cm is required for skiing, the season length has contracted by 28% relative to the historical period (1960’s) in the model. Relative to the 2000-2010 period it is projected to contract by 83% by the 2070’s.

A4 Changes to the frequency of suitable snowmaking conditions

The number of hours suitable for snowmaking (below -2°C) before the start of the ski season (June 3rd) at Mt Hotham declines from 164 hours in the 1960s to 22 by the end of the century resulting in less than 15% of the historical snowmaking opportunities remaining by the end of the century (Table 4.2A). This represents a drop of approximately 7% per decade, but the decline is as high as 18% in the 2020s, followed by further declines of approximately 13% in each of the next two decades. Opportunities for snowmaking relative to the 2010's are halved by 2030-2040.

If snow is made at warmer temperatures, more hours are available for snowmaking for longer into the future, but still decline to 43 hours below -1°C and 109 hours below 0.5°C by the final decade of the century.

The drop in conditions suitable for snowmaking throughout the year is presented graphically for the three wet bulb temperature thresholds (-2°C, -1°C, 0.5°C) in Figures 4.9A to 4.11A. Values for the decades 1960-2010 and 2070-2090 are based on the multi-model mean of 3 hourly data from the dynamically downscaled model runs, while the decades 2020-2060 are the multi-model mean of 3 hourly data from the statistically derived values (see Box 2 in the main report). The results show a gradual decline from 1960 to 2000, followed by a marked drop in available hours for snowmaking between the 2020's and 2030's. If warmer thresholds are accepted, with the associated trade-offs in cost and quality of snow, the number of hours suitable for making snow is higher than at colder temperatures.

The accumulation of hours below different threshold temperatures can be used to indicate the start of the ski season, and the quality of snow that may be made (Figures 4.9A to 4.11A). In the 1960's, approximately 180 hours below -2°C wet bulb temperature had accumulated, on average, before the ski season start date (3rd June). By 2020 this is projected to decline to 100 hours available for making snow. By 2070, less than 40 hours below -2°C accumulate before 3rd June. We use the 1960s value (350 hours below -2°C) to indicate the climatic beginning of the ski season (rather than the calendar date). In these terms, the changes equate to a relative shift in the start of the ski season from the 3rd June (1960's) to the 25th June in the 2020's and the 9th and 28th July in the 2030's and 2040's. By the end of the century, it would not be until the 6th October that the same number of snowmaking hours would accumulate.

As natural snow declines, more snow will need to be made, under warmer conditions, to achieve the target snow depth profile throughout the season (see Table 2 in the main report). At Mt Hotham, by 2070, almost all snow will need to be artificially produced, in approximately 70% fewer snowmaking hours (relative to 2010). However, if snow is made at warmer temperatures, snowmaking hours can be maintained at current (2010) levels until the 2030's (-1°C wet bulb temperature) or the 2090's (-0.5°C). For example, by the start of the season, at present (2010-2020 period) there are about 20 snowmaking hours below -2°C per week. By 2070 this drops to 6 hours, but if the warmer threshold of 0.5°C is used, 25 hours remain.

Table 4.1A: Projected change in key climate variables at Mt Hotham between the current (1961-2010) and future (2070-2099) time periods. The multi-model mean is shown for each 30 year period, with the range of change between climate models shown in brackets.

	Temperature (°C)			Wet bulb temperature (°C)			Precipitation (mm)		Snowfall (mm)		Wind speed (m/s)	Wind direction (m/s)
	Minimum Winter	Maximum Summer	Mean annual	Minimum Winter	Maximum Summer	Mean annual	Mean Daily	Mean Annual	Maximum weekly	Mean Annual Maximum	Mean annual	
Current	-4.60 (-4.67, -4.49)	26.15 (25.56, 26.63)	7.81 (7.69, 7.95)	-17.70 (-20, -15.49)	20.60 (20.21, 21.48)	5.17 (5.09, 5.27)	5.75 (5.62, 5.96)	2098.75	12.88 (8.47, 16.26)	669.76	2.97 (2.95, 2.99)	234.0 (232.5, 235.4)
Future	-1.43 (-1.84, -1.05)	31.51 (29.19, 33.42)	11.99 (10.94, 13.07)	-9.16 (-9.92, -7.89)	29.17 (25.01, 30)	8.68 (8.20, 9.26)	5.13 (4.50, 6.11)	1872.45	3.79 (1.17, 6.04)	197.08	2.95 (2.90, 3.00)	236.9 (234.2, 239.5)
Change	3.17 (2.76, 3.60)	5.36 (3.16 , 7.45)	4.18 (3.17, 5.38)	8.54 (5.93, 12.11)	8.56 (4.79, 9.75)	3.51 (3.06, 4.13)	-0.62 (-1.46, 0.49)	-11% (-20%, +3%)	-9.09 (-13.33, -2.43)	-71% (-86%,-63%)	-0.02 (-0.06, 0.03)	2.85 (0.57, 4.90)

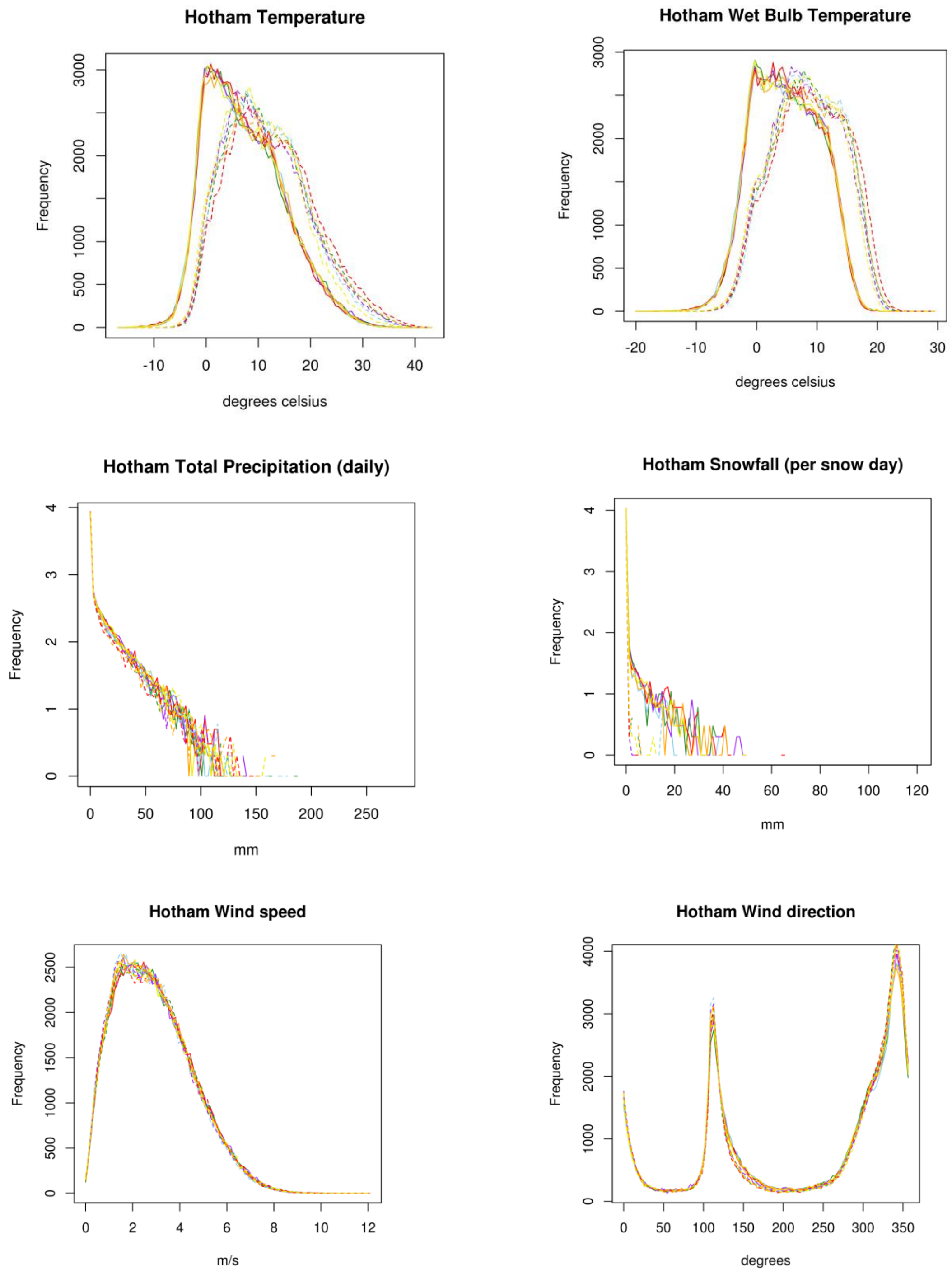


Figure 4.1A: Frequency distribution of key climate variables in the modelled current (full lines) and future (dashed lines) time periods. The six climate models are shown in different colours. log values for daily precipitation and snowfall are shown.

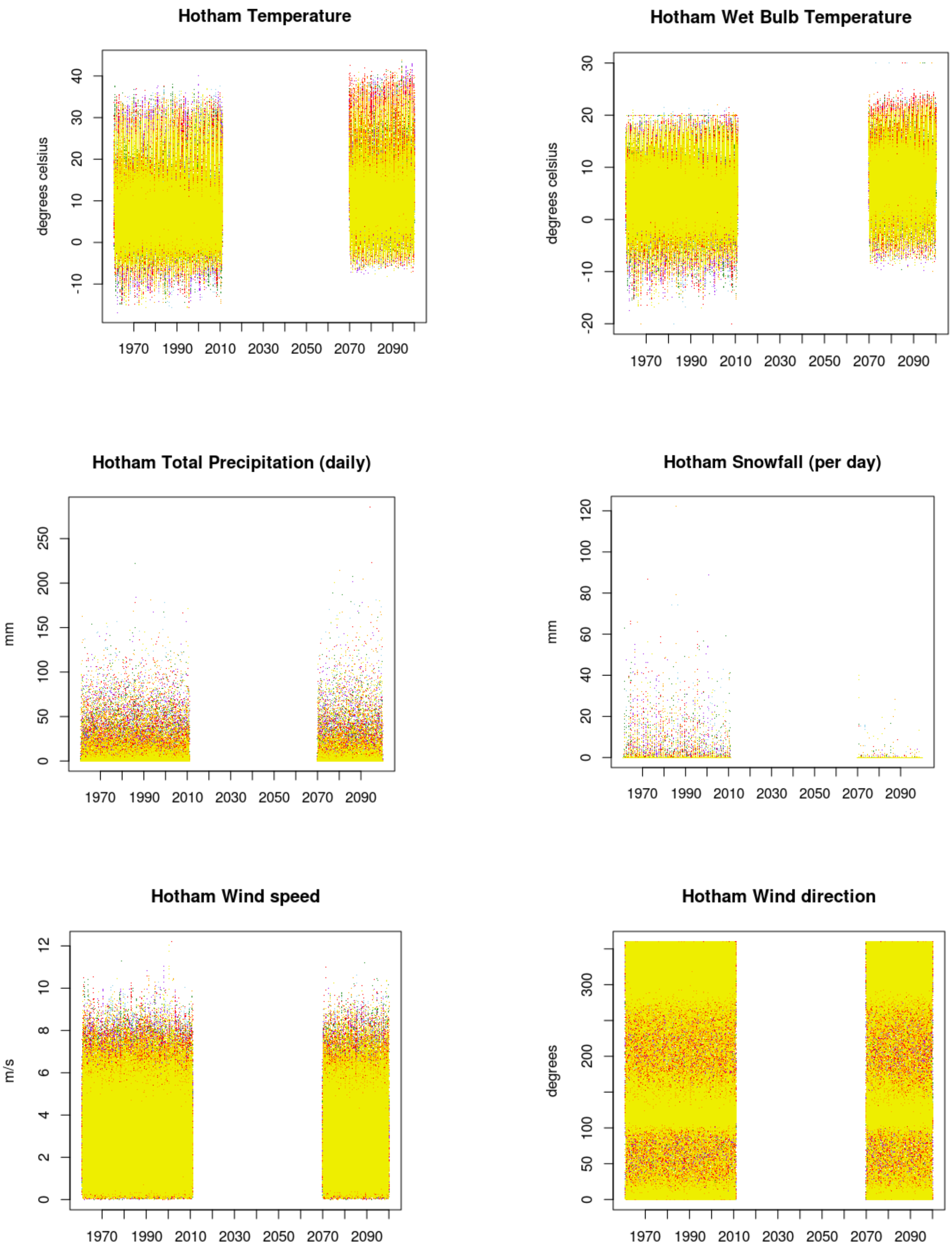


Figure 4.2A: Daily values of key climate variables from the six climate models showing the modelled periods, 1961-2010 and 2070-2099.

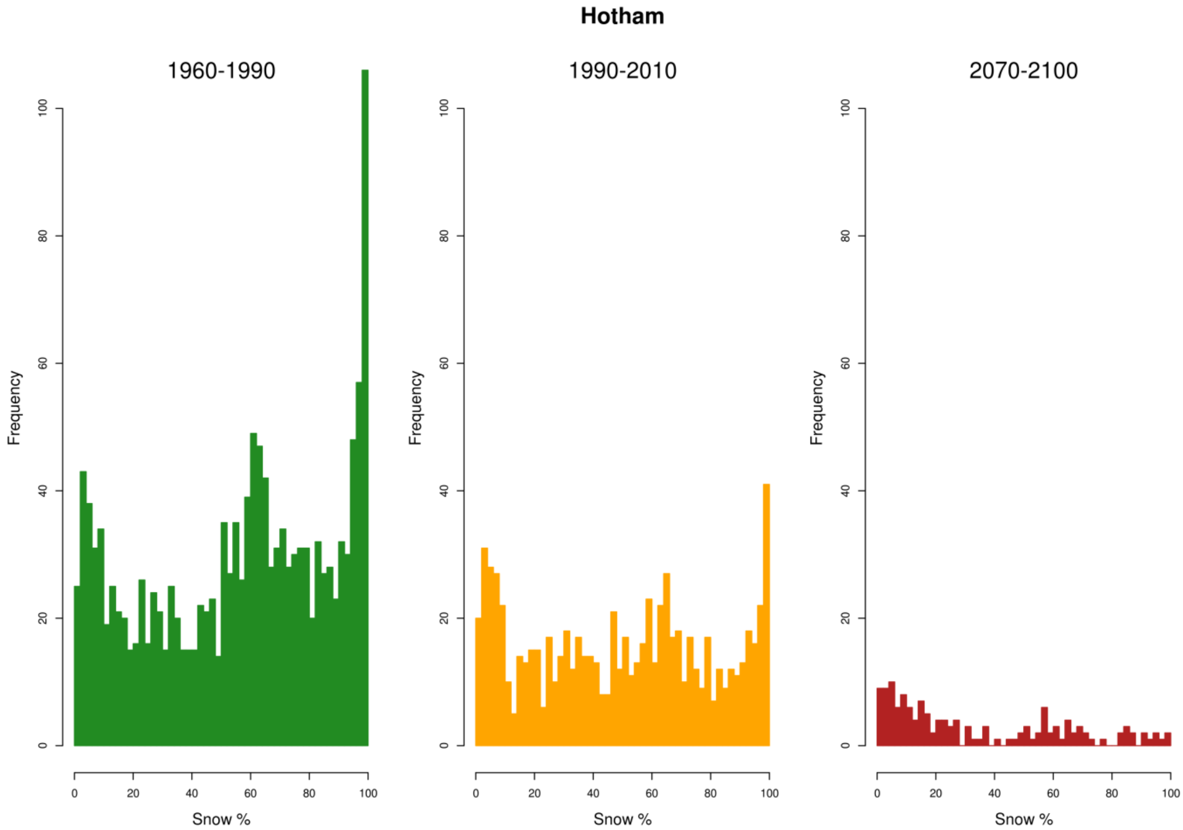
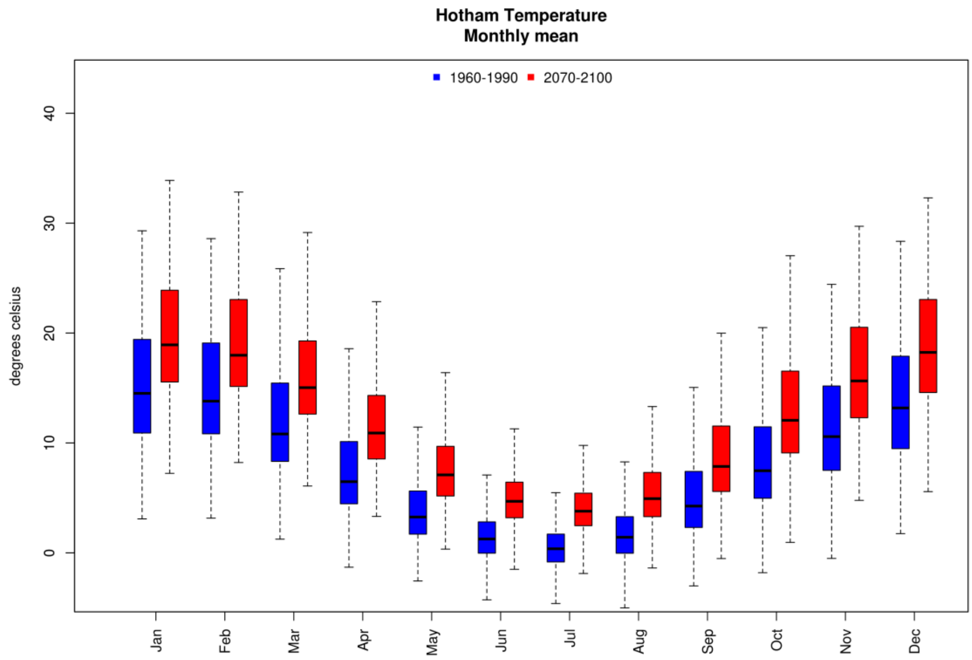
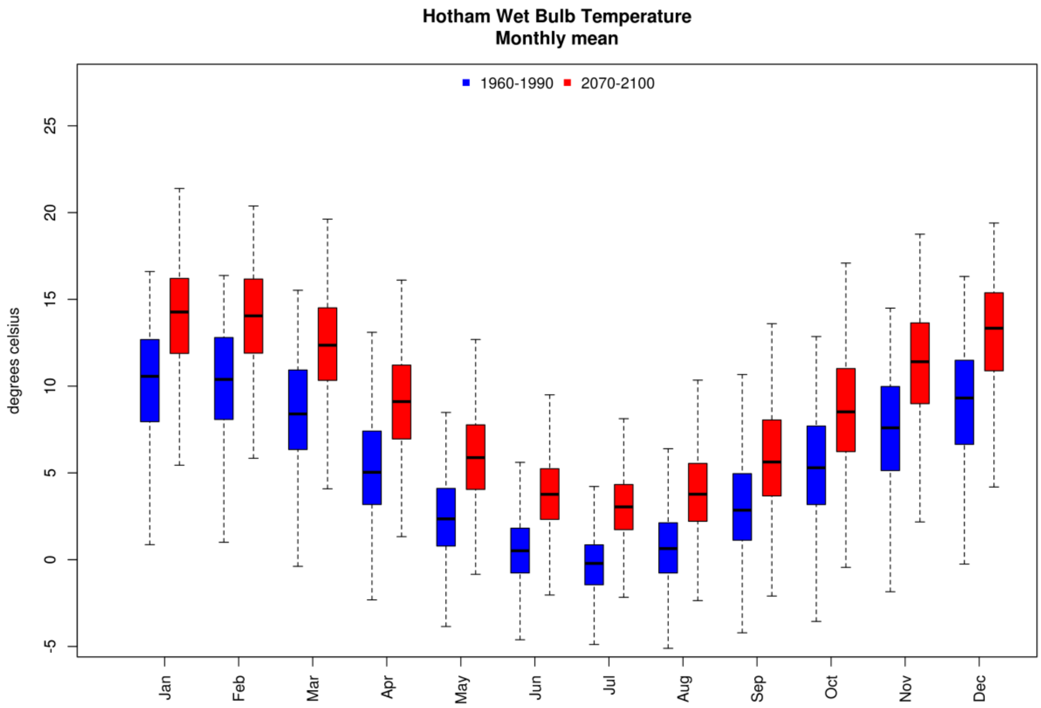
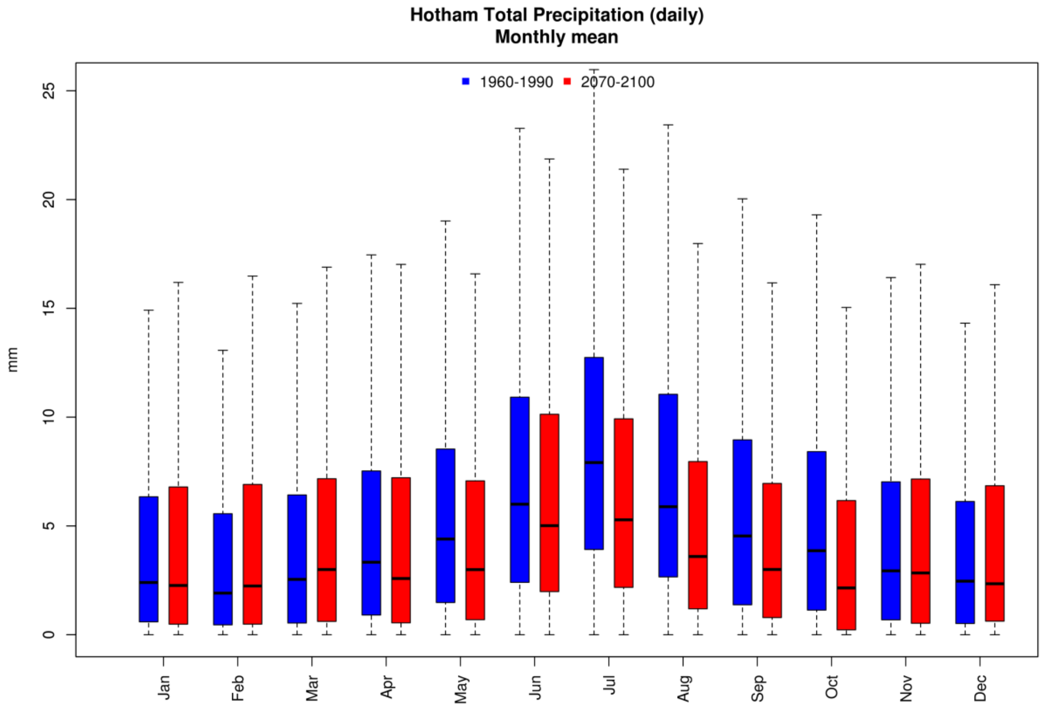
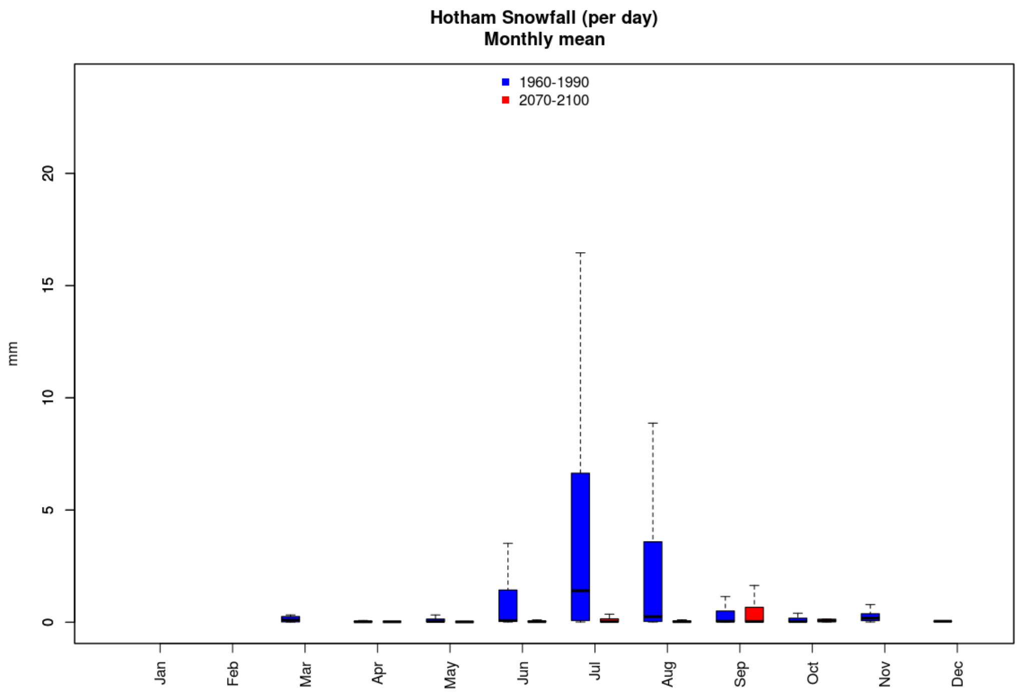


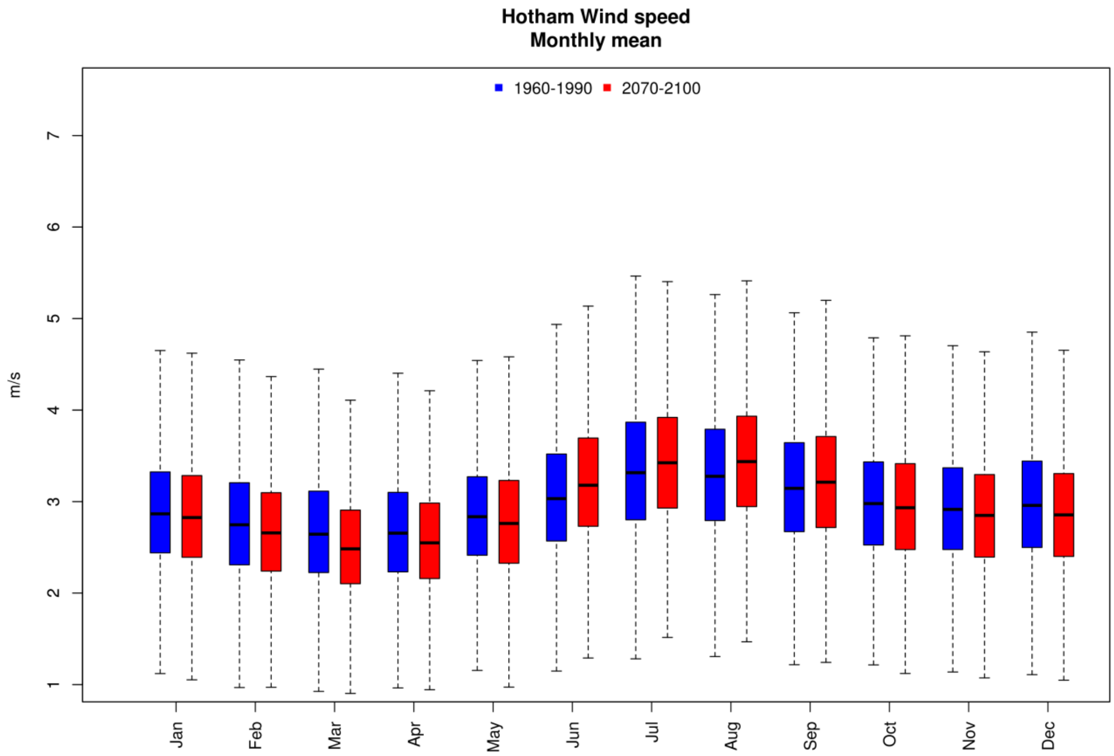
Figure 4.3A: The proportion of precipitation falling as snow in the historical (1960-1990), current (1990-2010) and future (2070-2100) periods.

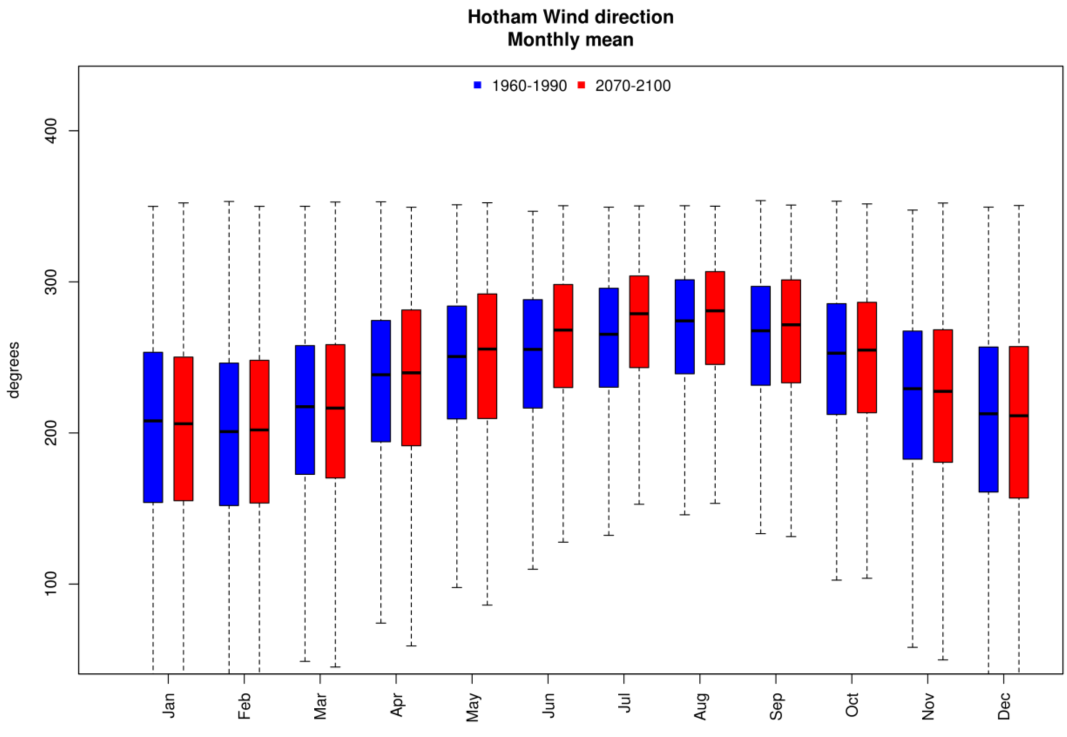

Hotham Temperature
Monthly mean
1960-1990
2070-2100
degrees celsius
0
10
20
30
40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Hotham Wet Bulb Temperature
Monthly mean
1960-1990
2070-2100
degrees celsius
-5
0
5
10
15
20
25
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Hotham Total Precipitation (daily)
Monthly mean
1960-1990
2070-2100
mm
0
5
10
15
20
25
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Hotham Snowfall (per day)
Monthly mean
1960-1990
2070-2100
mm
0
5
10
15
20
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Hotham Wind speed
Monthly mean
1960-1990
2070-2100
m/s
1
2
3
4
5
6
7
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Hotham Wind direction
Monthly mean
1960-1990
2070-2100
degrees
100
200
300
400
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

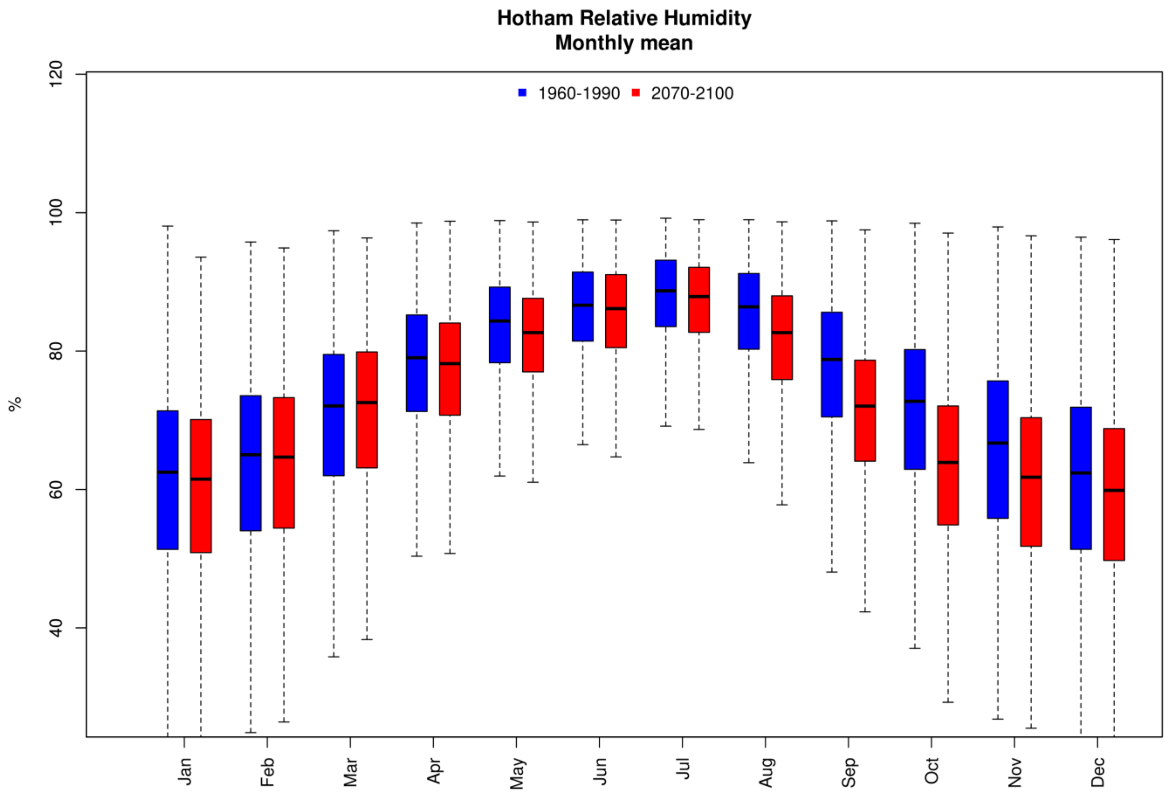


Figure 4.4A: The multi-model monthly mean values of key climate variables in the current (blue) and future (red) time periods. The bottom and top of the box are the 25th and 75th percentiles, the bar is the median, and the whiskers go to the most extreme data point which is no more than +/- 1.5 times the interquartile range from the box. Note that snowfall is the amount of snowfall on days when it snows.

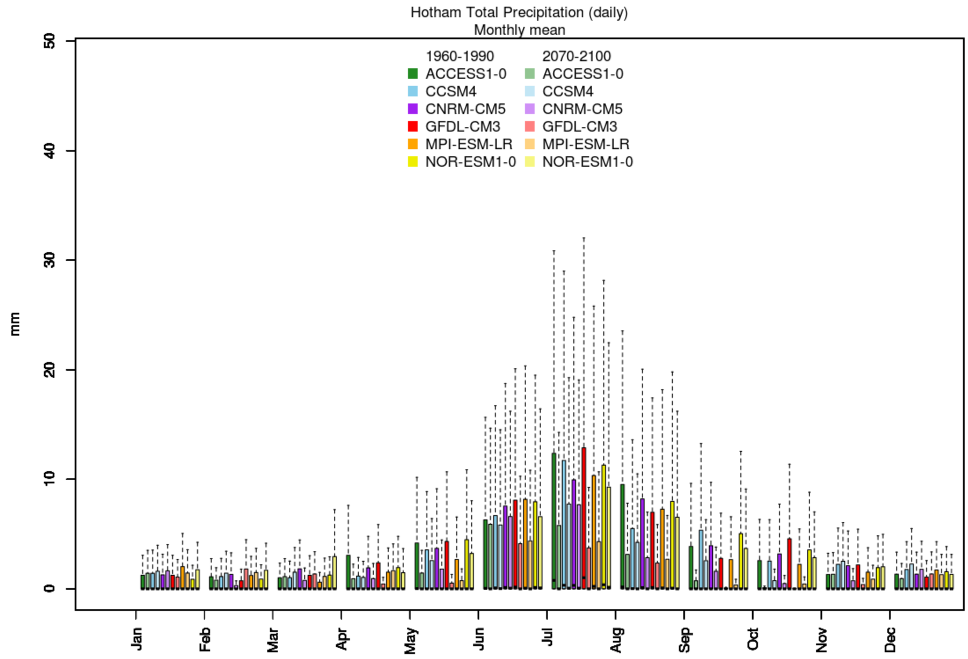


Figure 4.5A: The range in monthly mean precipitation projected by the six climate models in the current and future time periods.

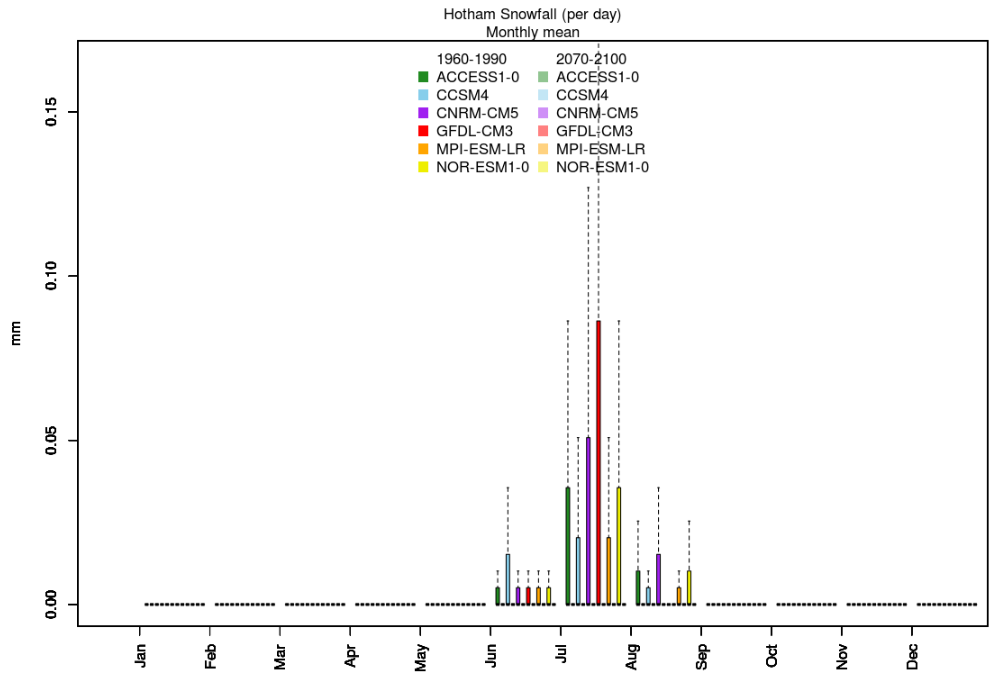


Figure 4.6A: The range in monthly mean snowfall projected by the six climate models in the current and future time periods.

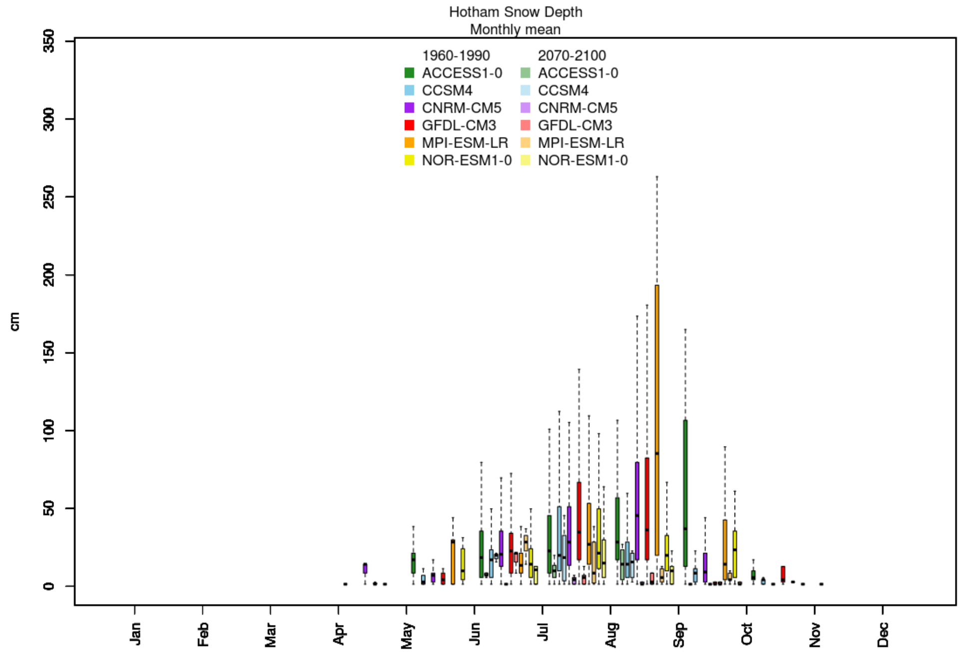


Figure 4.7A: The range in monthly mean snow depth projected by the six climate models in the current and future time periods.

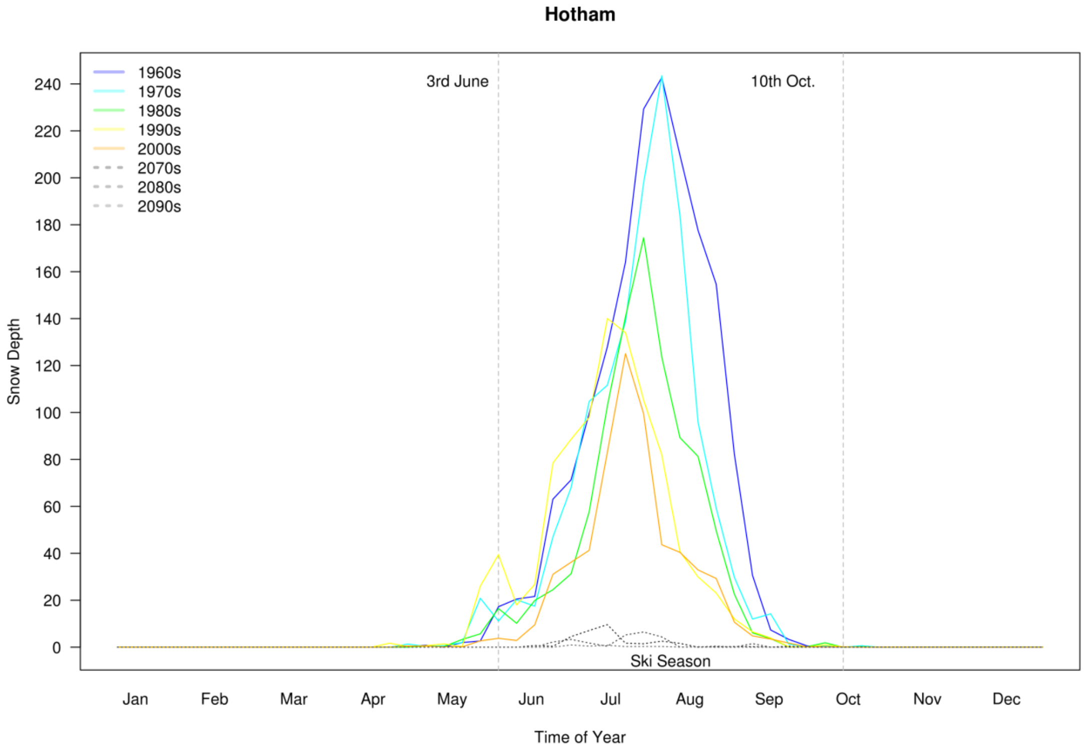


Figure 4.8C: The change in the ski season between current and future periods based on natural snow depth.

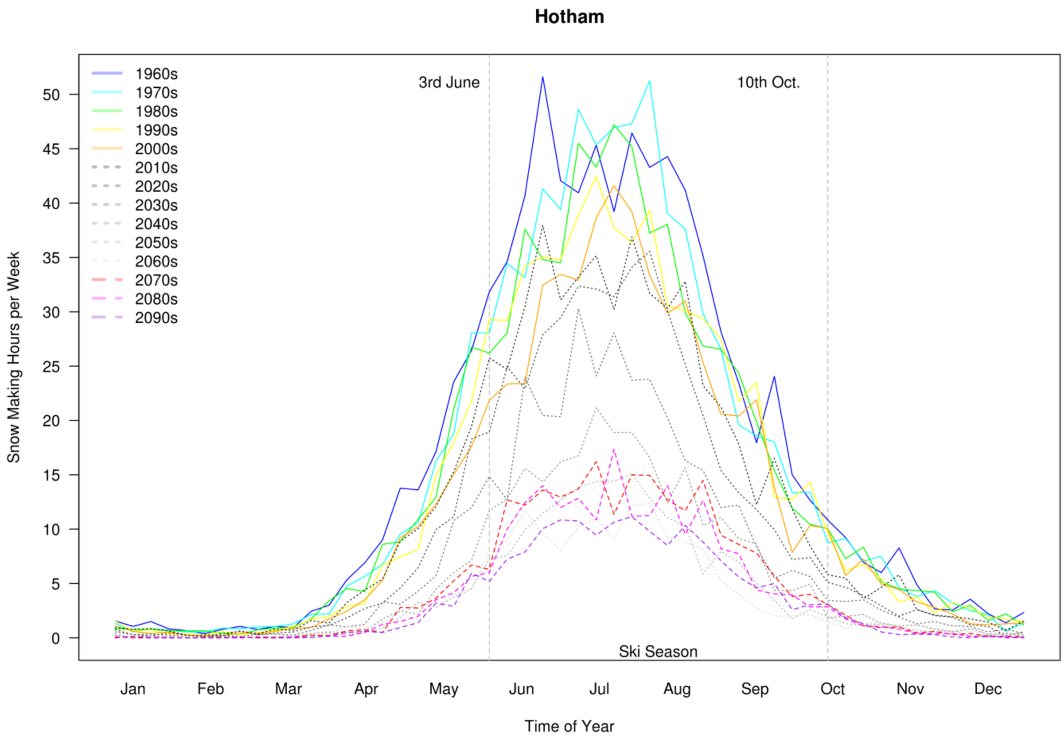
Table 4.2A: The number of snowmaking hours that accumulate at Mt Hotham by June 3rd based on three different thresholds for wet bulb temperatures (-2°C, -1°C, 0.5°C). Numbers in brackets show the range across the climate models. Values for the decades 1960-2010 and 2070-2090 are based on 3 hourly model output while the decades 2020-2060 are statistically derived.

Decade	**Number of hours above Wet Bulb temperature threshold**		
	-2°C	**-1°C**	**0.5°C**
1960s	164 (137 to 207)	272 (235 to 328)	494 (441 to 569)
1970s	142 (132 to 156)	241 (232 to 255)	445 (426 to 462)
1980s	137 (115 to 159)	227 (200 to 248)	421 (388 to 444)
1990s	123 (102 to 135)	205 (178 to 221)	392 (357 to 412)
2000s	106 (93 to 120)	185 (163 to 209)	368 (319 to 408)
2010s	114 (93 to 130)	195 (168 to 211)	388 (364 to 424)
2020s	84 (71 to 95)	152 (132 to 165)	314 (293 to 331)
2030s	61 (40 to 80)	113 (80 to 140)	250 (197 to 276)
2040s	39 (30 to 49)	78 (62 to 92)	181 (155 to 202)
2050s	27 (20 to 31)	56 (44 to 63)	140 (104 to 162)
2060s	30 (26 to 35)	60 (57 to 64)	142 (125 to 165)
2070s	30 (27 to 34)	61 (58 to 67)	150 (142 to 162)
2080s	25 (13 to 34)	52 (29 to 71)	127 (95 to 159)
2090s	22 (17 to 28)	43 (33 to 57)	109 (83 to 146)

Table 4.3A: Shift in ski season start date at Mt Hotham for three different thresholds for wet bulb temperatures (-2°C, -1°C, 0.5°C). Numbers in brackets show the range across the climate models. Values for the decades 1960-2010 and 2070-2090 are based on 3 hourly model output while the decades 2020-2060 are statistically derived. NA indicates that the season start date shifts to after the end of the current season (10th October).

Decade	**Shift in season start date relative to the 1960's (Days)**		
	-2°C	**-1°C**	**0.5°C**
1970s	4 (0 to 9)	4 (0 to 9)	4 (0 to 9)
1980s	6 (7 to 7)	7 (7 to 10)	7 (6 to 10)
1990s	9 (8 to 14)	11 (9 to 15)	10 (8 to 15)
2000s	16 (14 to 21)	15 (14 to 21)	13 (14 to 16)
2010s	13 (13 to 17)	13 (12 to 16)	11 (8 to 13)
2020s	22 (22 to 28)	22 (23 to 27)	19 (18 to 22)
2030s	33 (40 to 34)	34 (39 to 34)	31 (33 to 34)
2040s	52 (54 to 53)	52 (54 to 58)	47 (50 to 49)
2050s	80 (69 to 104)	76 (68 to 85)	63 (61 to 66)
2060s	113 (NA to 89)	82 (101 to 74)	67 (70 to 62)
2070s	68 (66 to 71)	63 (61 to 65)	55 (54 to 57)
2080s	79 (126 to 80)	70 (95 to 66)	62 (70 to 57)
2090s	122 (NA to 110)	94 (NA to 91)	79 (91 to 78)

a)



b)

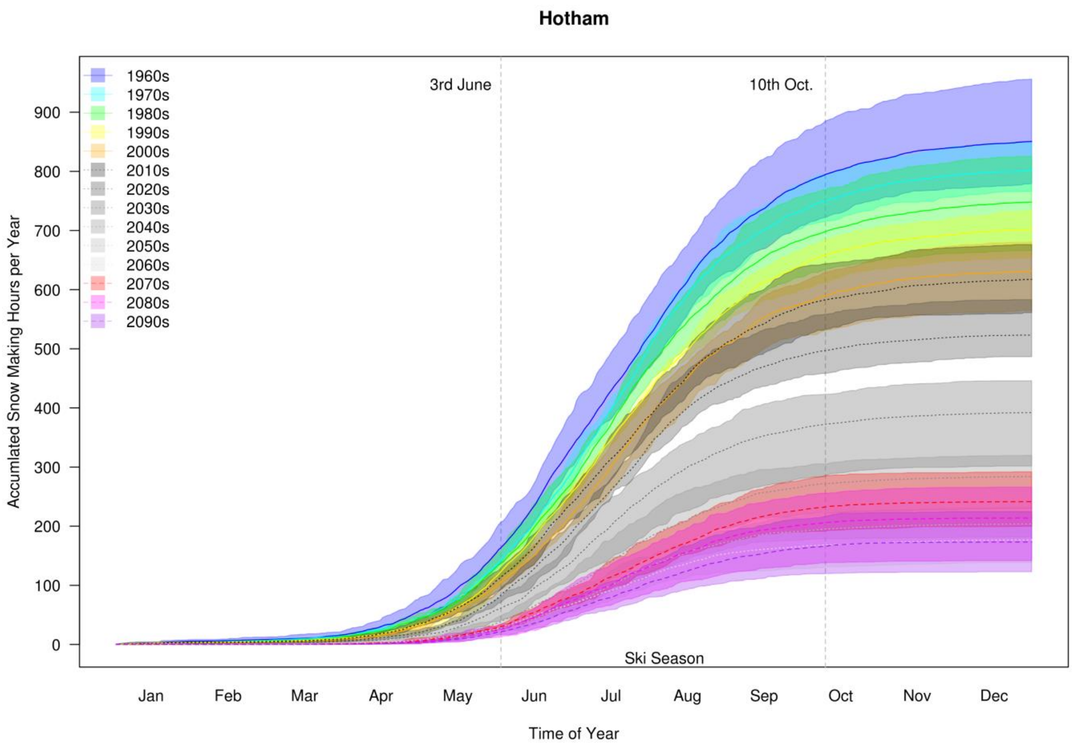
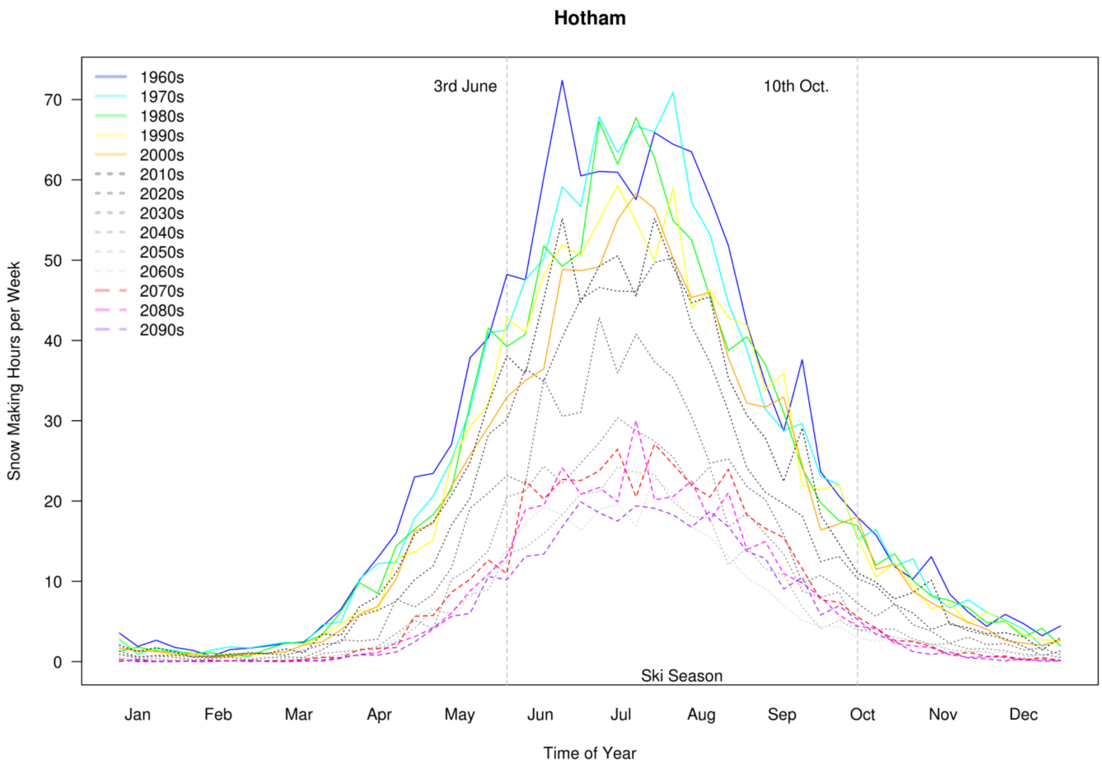


Figure 4.9A: The change in the number of hours suitable for snowmaking between current and future periods based on a threshold of -2°C wet bulb temperature. a) The number of hours per week below the threshold, b) Accumulated snowmaking hours per year

a)



b)

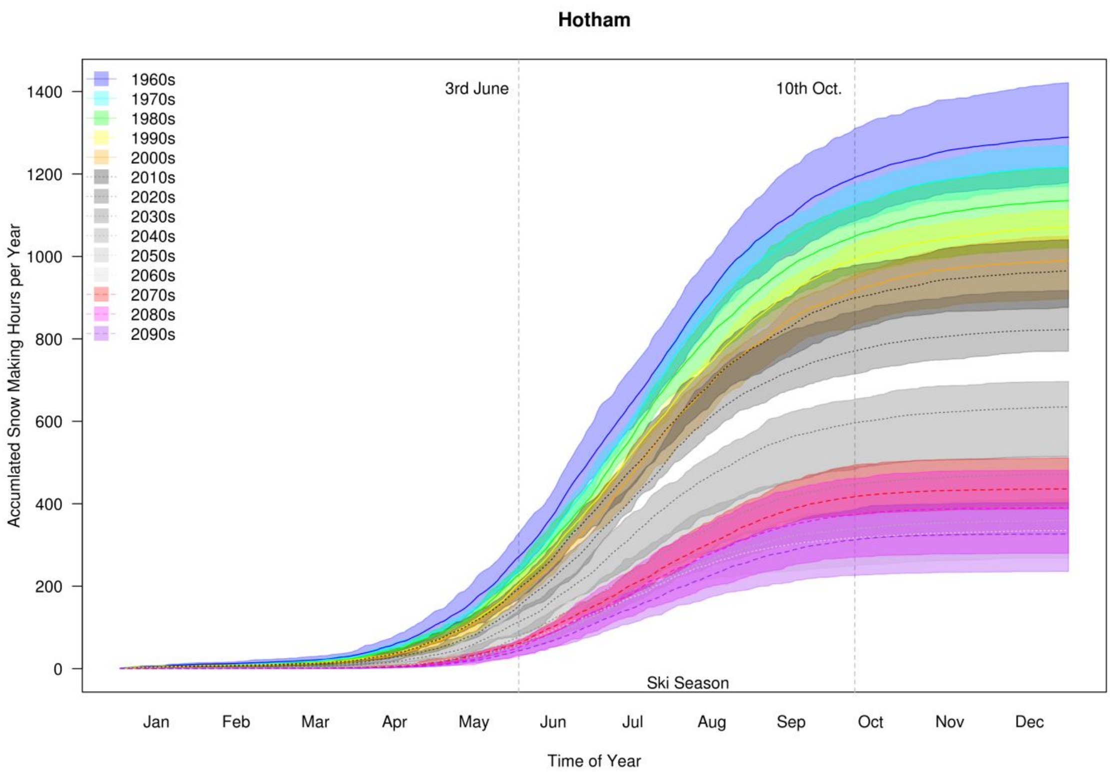
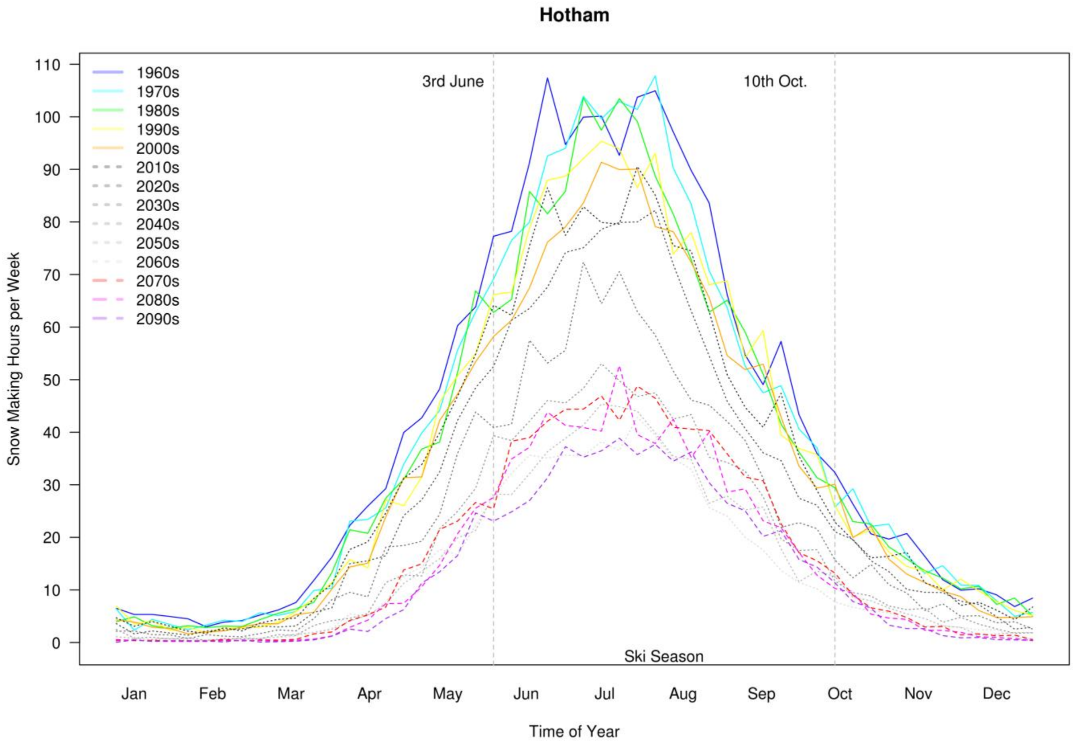


Figure 4.10A: The change in the number of hours suitable for snowmaking between current and future periods based on a threshold of -1°C wet bulb temperature. a) The number of hours per week below the threshold, b) Accumulated snowmaking hours per year

a)



b)

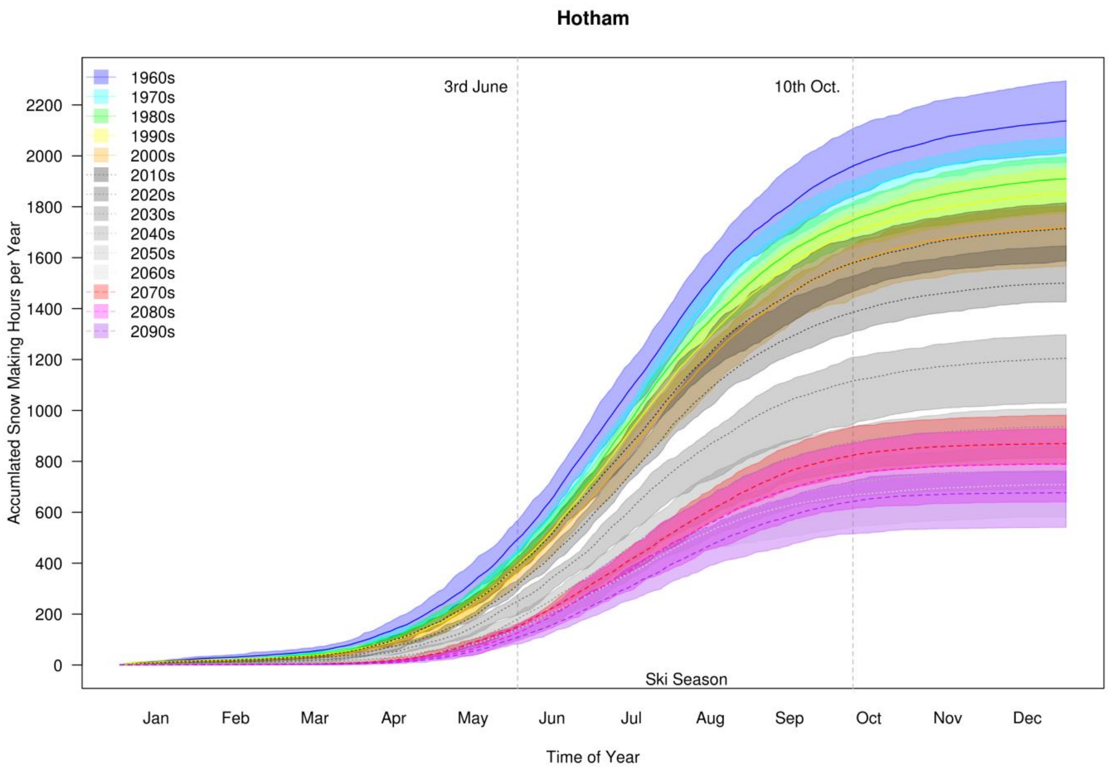


Figure 4.11A: The change in the number of hours suitable for snowmaking between current and future periods based on a threshold of 0.5°C wet bulb temperature. a) The number of hours per week below the threshold, b) Accumulated snowmaking hours per year

B. MT BULLER (elevation 1809m)

This section describes the changes in climate that are projected to occur at the Mt Buller resort. An explanation of the Climate Futures for the Australian Alps projections, the methods used and results from across all of the Victorian Alpine resorts can be found in the main report. The main report also provides important information about the scope of the study and considers the uncertainty associated with projections of future climate.

Relative to recent decades (1961-2010), the projections for Mt Buller by the end of the century, under a high emissions scenario, show:

1. An increase in mean annual temperature of 3-5°C (mean of 4°C);
2. An increase in the number of extreme hot temperatures and a decrease in the number of very cold days;
3. The temperature of the coldest days in winter increases by approximately 3°C, while the temperature of the hottest summer days increase by approximately 5°C;
4. A mean decrease in annual precipitation of 7%. However, a maximum decrease of 13% to a slight increase of +6% is shown across the six climate models;
5. A decrease in precipitation from April to September for all climate models;
6. Substantial reductions in snowfall, from 86% to 70% less snowfall than the baseline period (mean reduction of 74%);
7. With warmer temperatures there is a reduction in the proportion of precipitation falling as snow. More snow falling as sleet has implications for the retention of snow;
8. No change in wind speed or wind direction.

B1 Changes between current and future periods

The changes projected to occur at Mt Buller between the current (1961-2010) and future (2070-2099) time periods are shown in Table 4.1B.

Figure 4.1B shows the frequency distribution for key climate variables in the modelled current (1961-2010) and future (2069-2099) time periods. The number of occurrences of a particular value is used to highlight any shifts in the overall distribution, the mean or the variance (spread) of the values for each climate variable. The daily values across all models are shown in Figure 4.2B.

The proportion of precipitation falling as snow in the historical, current and future periods are shown in Figure 4.3B. Fewer snow days in the future means that there will be fewer days when precipitation is 100% snow. There is also a reduction in the proportion of snow, with more snow falling as sleet. This has implications for the retention of natural or artificial snow.

B2 Changes to monthly mean values

A comparison of the multi-model mean monthly values of key climate variables in the current and future time periods is presented in Figure 4.4B. Increases in temperature are evident in every month of the year. In the future, the monthly mean temperature of the winter months, (June, July and August) is projected to be more like that currently experienced in autumn and spring. Temperatures in June, July and August in the future are projected to be similar to those currently experienced in May or September. May and September in the future period show temperatures similar to those currently experienced in April or October. This could potentially affect the ability for artificial snow to be laid down in the months leading up to the ski season.

Similarly, mean monthly wet bulb temperatures increase in all months, and show the same shifts in winter towards temperatures currently more typical of autumn and spring. Wet bulb temperature does not increase as much as dry bulb temperature, however, because wet bulb temperature reflects the influence of humidity. Note that this summary of monthly values does not show the very low temperatures because it is based on daily means. More detailed analyses of the number of hours per day suitable for snowmaking at particular threshold temperatures are provided in Section B4.

There are no changes to wind speed or direction in any month of the year. Projections of humidity, however, which showed no change in annual means, is projected to decrease slightly in June and July, with more substantial reductions evident in April, May, August and September (Figure 4.4B).

The large range in monthly values for precipitation is due to the range in values across the six climate models (Table 4.1B). However, all models project decreased precipitation to occur during the months April through to September (Figure 4.5B). In the other months, there is more inconsistency in the direction of change, with some models showing slight increases and others decreases. Substantial reductions in snowfall and snow depth are projected by all climate models in all months (Figure 4.6B, Figure 4.7B). Not only are there fewer days when it snows, but there is reduced snowfall on days when it does snow.

B3 Shifts in the timing and duration of the ski season based on natural snow

The change in the duration and timing of the ski season between current and future periods based on natural snow depth is shown in Figure 4.8B.

All models agrees with observational records that indicate a steady reduction in snow depth over recent decades, from the 1960’s to 2010’s, and the duration of the ski season has contracted, with a later start and earlier finish. Assuming a depth of 30cm is required for skiing, the season length has contracted by 18% relative to the historical period (1960’s) in the model. Relative to the 2000-2010 period, it is projected to contract by 88% by the 2070’s.

B4 Changes to the frequency of suitable snowmaking conditions

The number of hours suitable for snowmaking (below -2°C) before the start of the ski season (June 3rd) at Mt Buller declines from 130 hours in the 1960s to 11 by the end of the century resulting in only 8% of the historical snowmaking opportunities remaining by the end of the century (Table 4.2B). This represents a drop of approximately 7% per decade, but the decline is as high as 20% in the 2020s, followed by further declines of 10% in the 2030's and 16% in the 2040's. Opportunities for snowmaking relative to the 2010's are halved by 2030-2040.

If snow is made at warmer temperatures, more hours are available for snowmaking for longer into the future, but still decline to 27 hours below -1°C and 11 hours below 0.5°C by the final decade of the century.

The drop in conditions suitable for snowmaking throughout the year is presented graphically for the three wet bulb temperature thresholds (-2°C, -1°C, 0.5°C) in Figures 4.9B to 4.11B. Values for the decades 1960-2010 and 2070-2090 are based on the multi-model mean of 3 hourly data from the dynamically downscaled model runs, while the decades 2020-2060 are the multi-model mean of 3 hourly data from the statistically derived values (see Box 2 in the main report). The results show a gradual decline from 1960 to 2000, followed by a marked drop in available hours for snowmaking between the 2020's and 2030's. If warmer thresholds are accepted, with the associated trade-offs in cost and quality of snow, the number of hours suitable for making snow is higher than at colder temperatures.

The accumulation of hours below different threshold temperatures can be used to indicate the start of the ski season, and the quality of snow that may be made (Figures 4.9B to 4.11B). In the 1960's, approximately 130 hours below -2°C wet bulb temperature had accumulated, on average, before the ski season start date (3rd June). By 2020 this is projected to decline to 80 hours available for making snow. By 2070, the number of hours below -2°C accumulated before 3rd June is close to zero. We use the 1960s value (350 hours below -2°C) to indicate the climatic beginning of the ski season (rather than the calendar date). In these terms, the changes equate to a relative shift in the start of the ski season from the 3rd June (1960's) to the 28th June in the 2020's and the 14th July and 9th August in the 2030's and 2040's. By the end of the century, the season start date based on accumulated snowmaking hours shifts to after the end of the current season (10th October).

As natural snow declines, more snow will need to be made, under warmer conditions, to achieve the target snow depth profile throughout the season (see Table 2 in the main report). At Mt Buller, by 2070, almost all snow will need to be artificially produced, in approximately 75% fewer snow making hours (relative to 2010). However, if snow is made at warmer temperatures, snowmaking hours can be maintained at current (2010) levels until the 2030's (-1°C wet bulb temperature) or the 2090's (-0.5°C). For example, by the start of the season, at present (2010) there are about 28 snowmaking hours below -2°C per week. By 2070 this drops to 8 hours, but if the warmer threshold of 0.5°C is used, almost 20 hours remain.

Table 4.1B: Projected change in key climate variables at Mt Buller between the current (1961-2010) and future (2070-2099) time periods. The multi-model mean is shown for each 30 year period, with the range of change between climate models shown in brackets.

	Temperature (°C)			Wet bulb temperature (°C)			Precipitation (mm)		Snowfall (mm)		Wind speed (m/s)	Wind direction (m/s)
	Minimum Winter	Maximum Summer	Mean annual	Minimum Winter	Maximum Summer	Mean annual	Mean Daily	Mean Annual	Maximum weekly	Mean Annual Maximum	Mean annual	
Current	-3.83 (-3.96, -3.70)	27.06 (26.50 , 27.59)	8.57 (8.43 , 8.69)	-14.19 (-17.86, -11.62)	21.26 (20.63, 21.62)	5.66 (5.58, 5.78)	3.66 (3.60, 3.72)	1335.9	8.39 (6.78, 9.93)	436.28	3.03 (3.01, 3.05)	232.59 (231.20, 234.36)
Future	-0.98 (-1.46, -0.51)	32.22 (30.12 , 34.11)	12.74 (11.65, 13.81)	-9.32 (-10.71, -8.27)	30 (30, 30)	9.10 (8.62, 9.66)	3.39 (3.14, 3.93)	1237.35	2.19 (0.94, 3.28)	113.88	3.03 (2.96, 3.10)	231.79 (227.92, 234.95)
Change	2.85 (2.34, 3.44)	5.15 (3.13 , 7.27)	4.17 (3.10, 5.38)	4.87 (2.64, 8.86)	8.74 (8.38, 9.37)	3.44 (2.98, 4.06)	-0.27 (-0.58, 0.33)	-7% (-13%, +6%)	-6.20 (-7.87, -4.15)	-74% (-86%,-70%)	0 (-0.07, 0.05)	-0.81 (-5.57, 3.42)

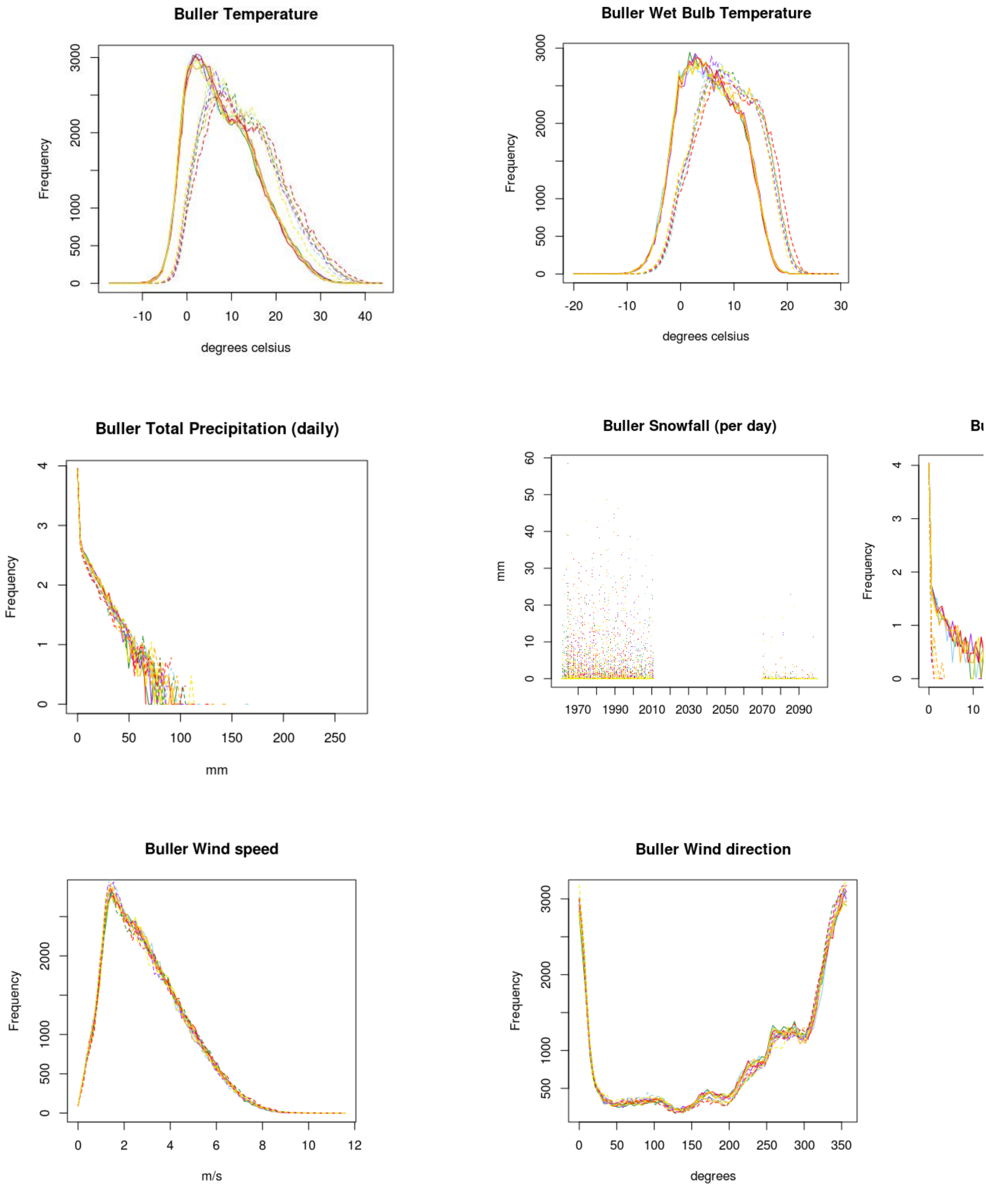


Figure 4.1B: Frequency distribution of key climate variables in the modelled current (full lines) and future (dashed lines) time periods. The six climate models are shown in different colours. log values for daily precipitation and snowfall are shown.

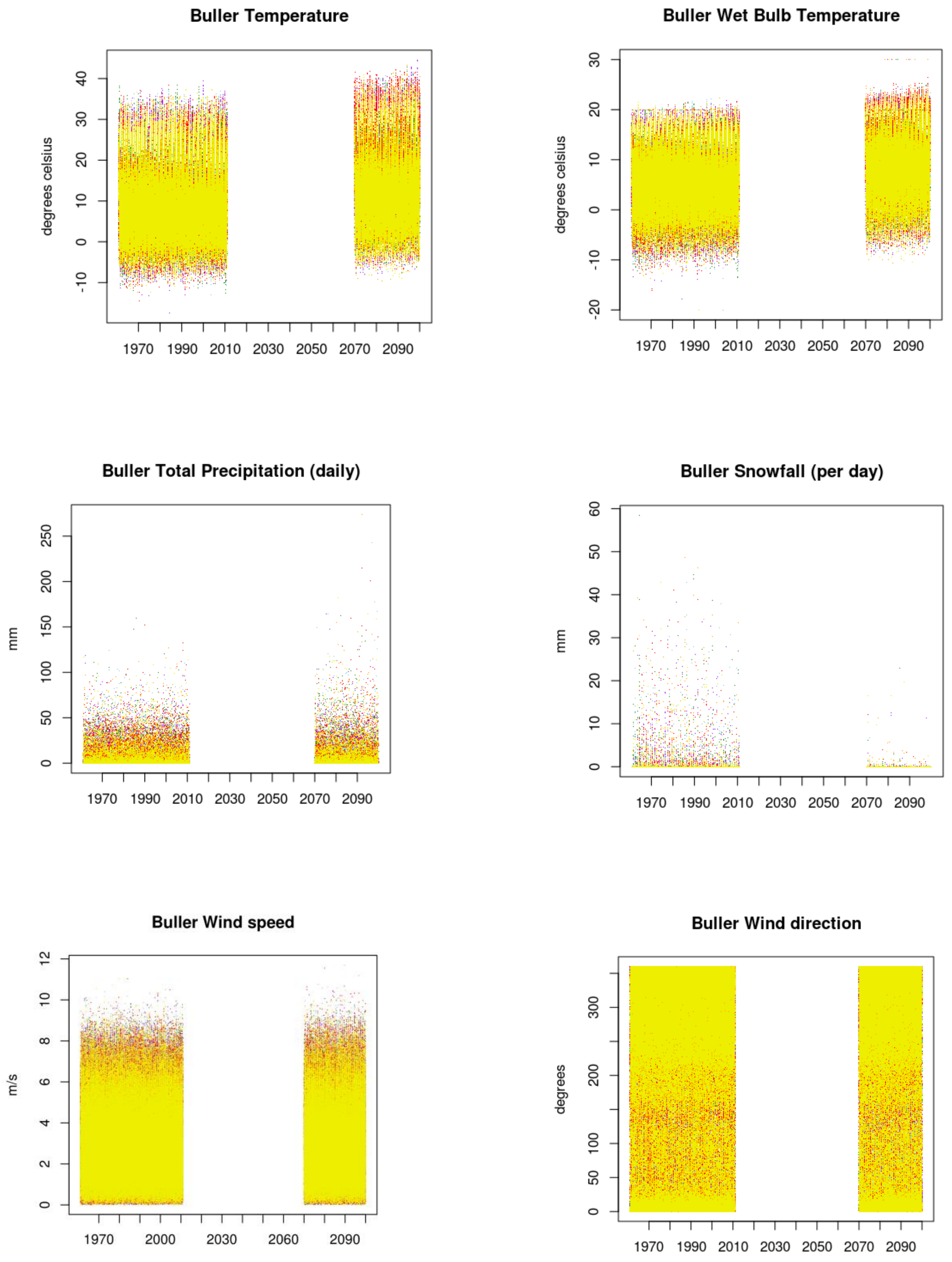


Figure 4.2B: Daily values of key climate variables from the six climate models showing the modelled periods, 1961-2010 and 2070-2099.

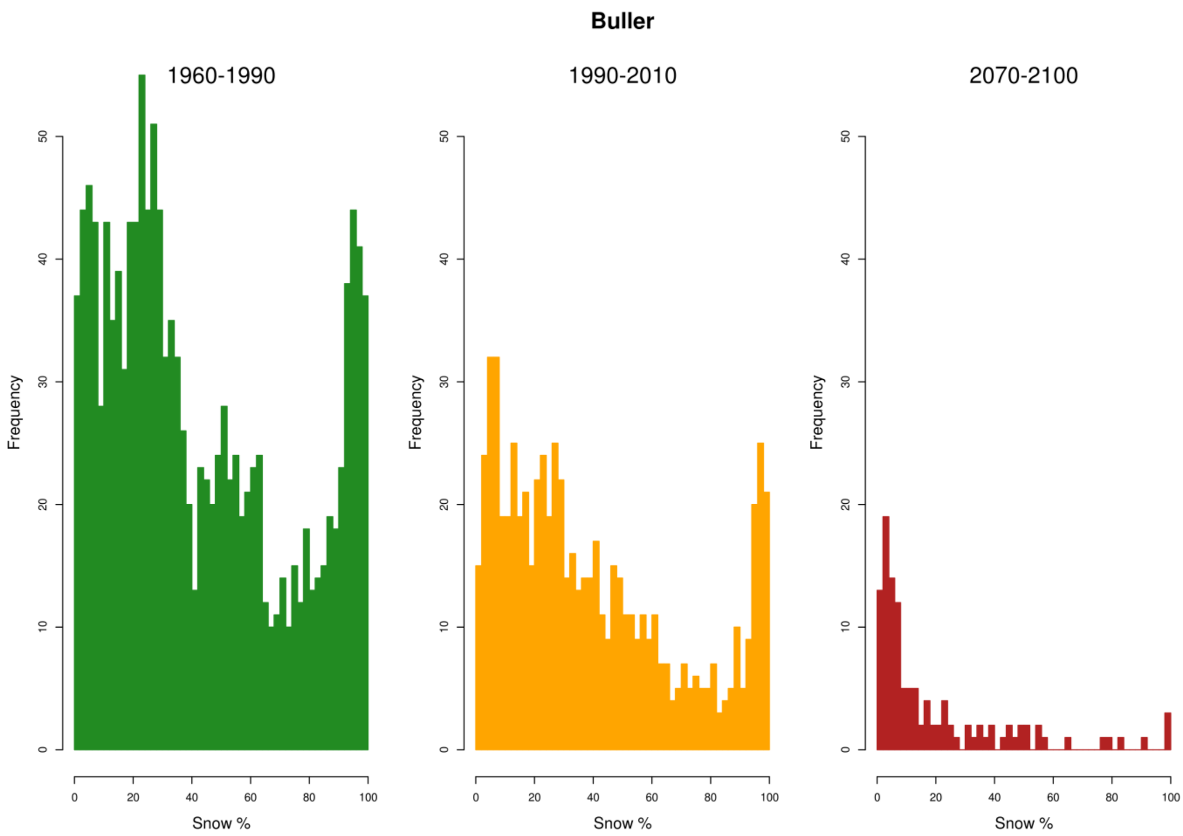
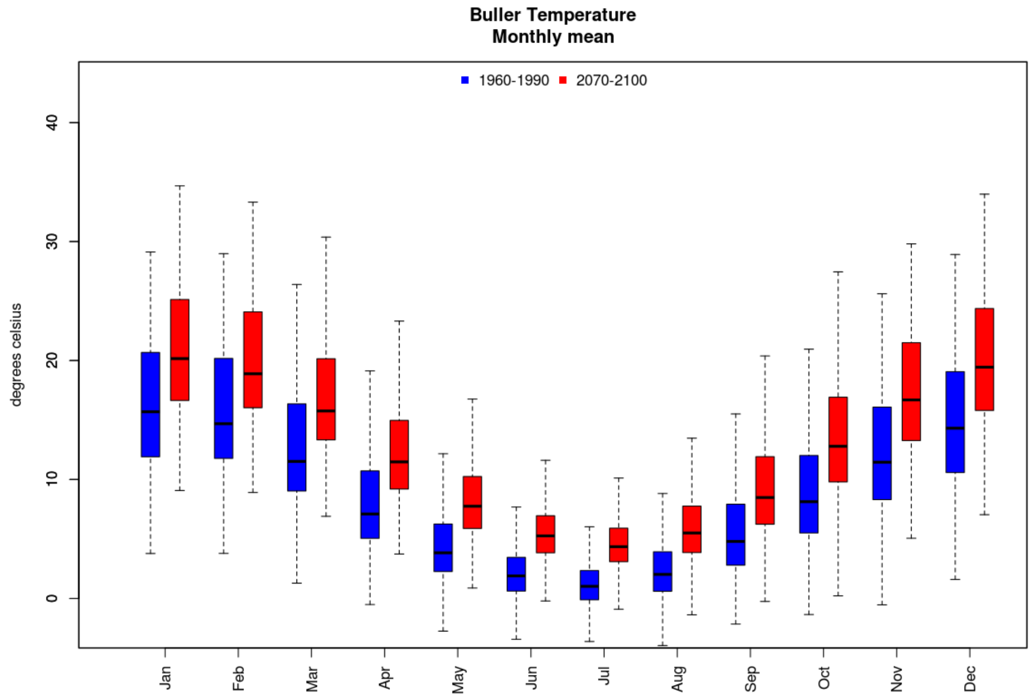
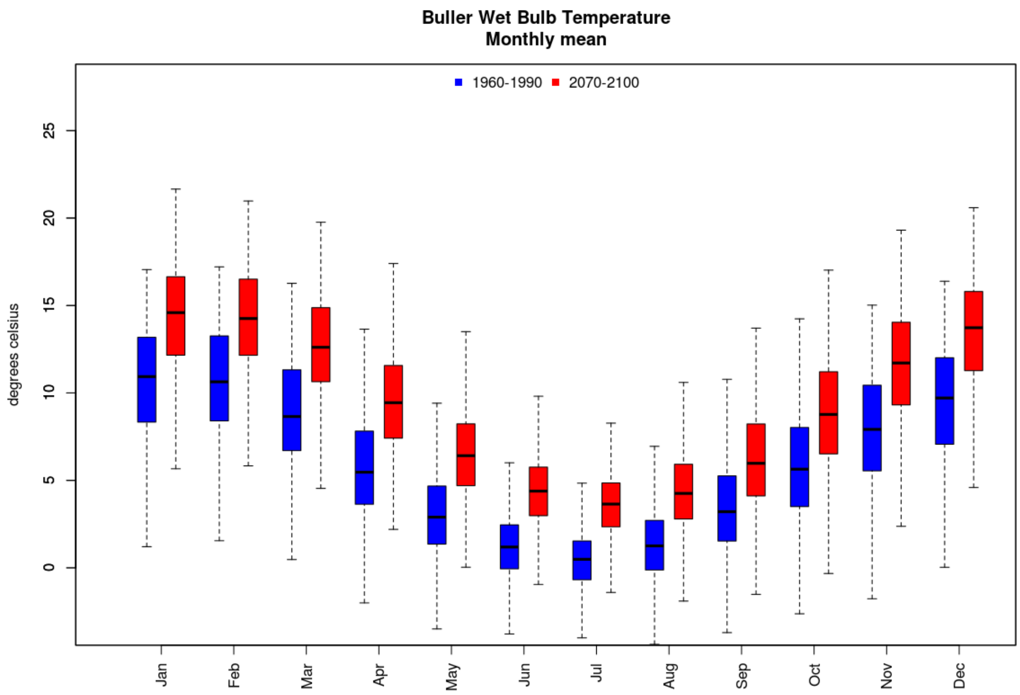
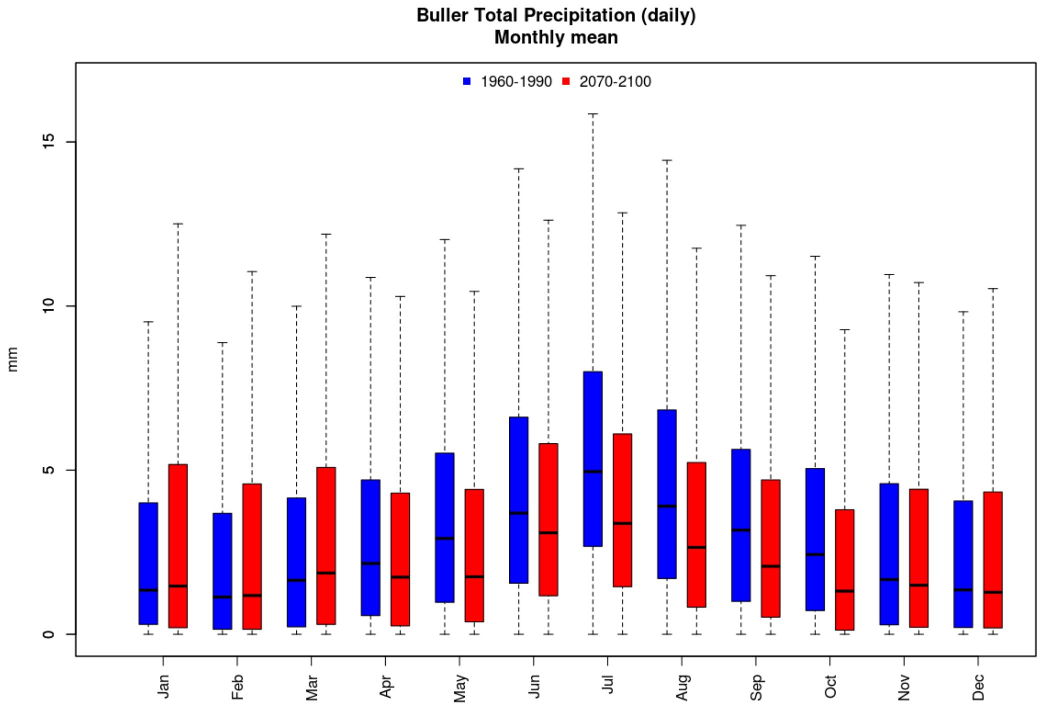
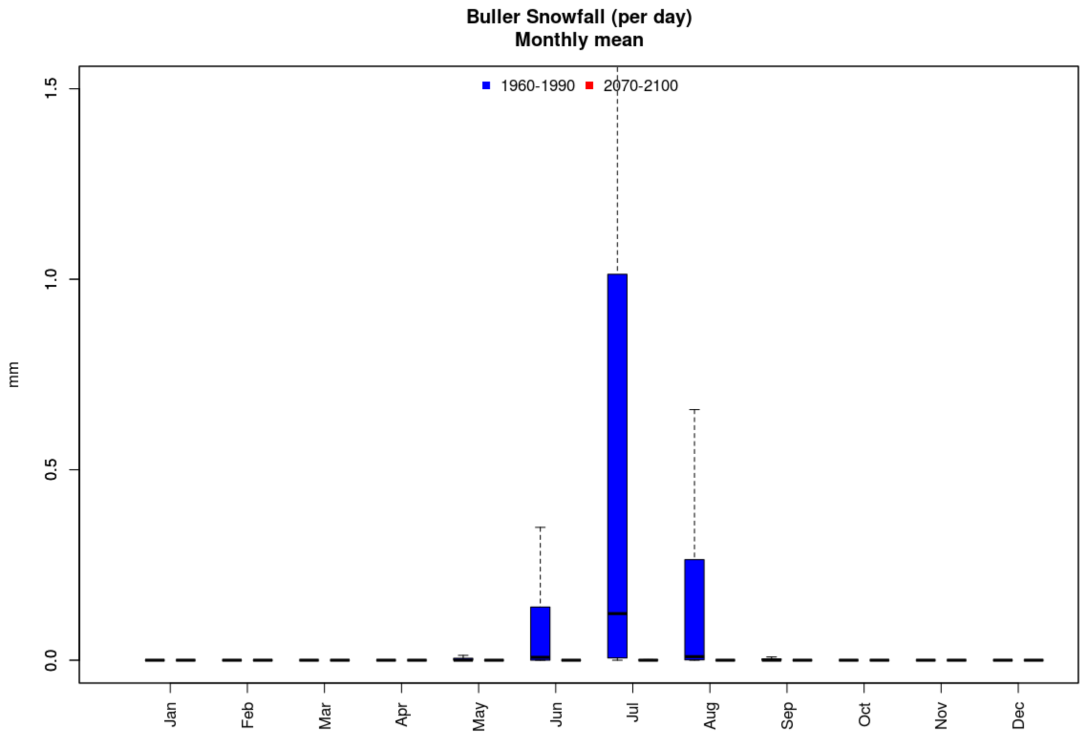


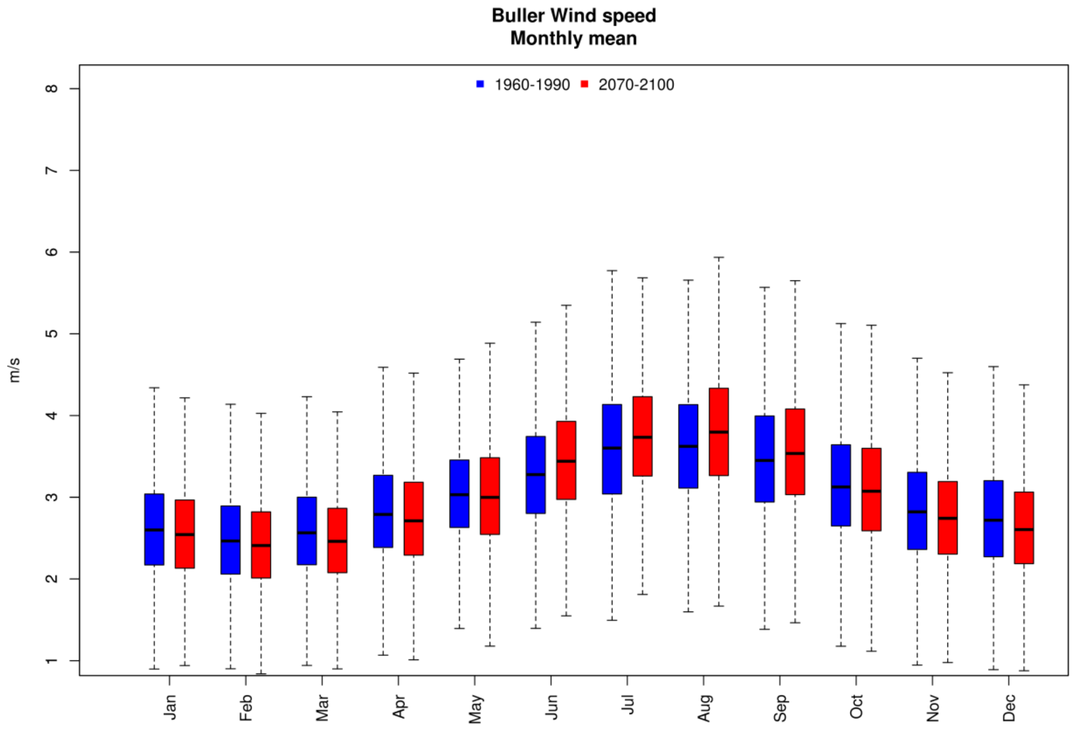
Figure 4.3B: The proportion of precipitation falling as snow in the historical (1960-1990), current (1990-2010) and future (2070-2100) periods.

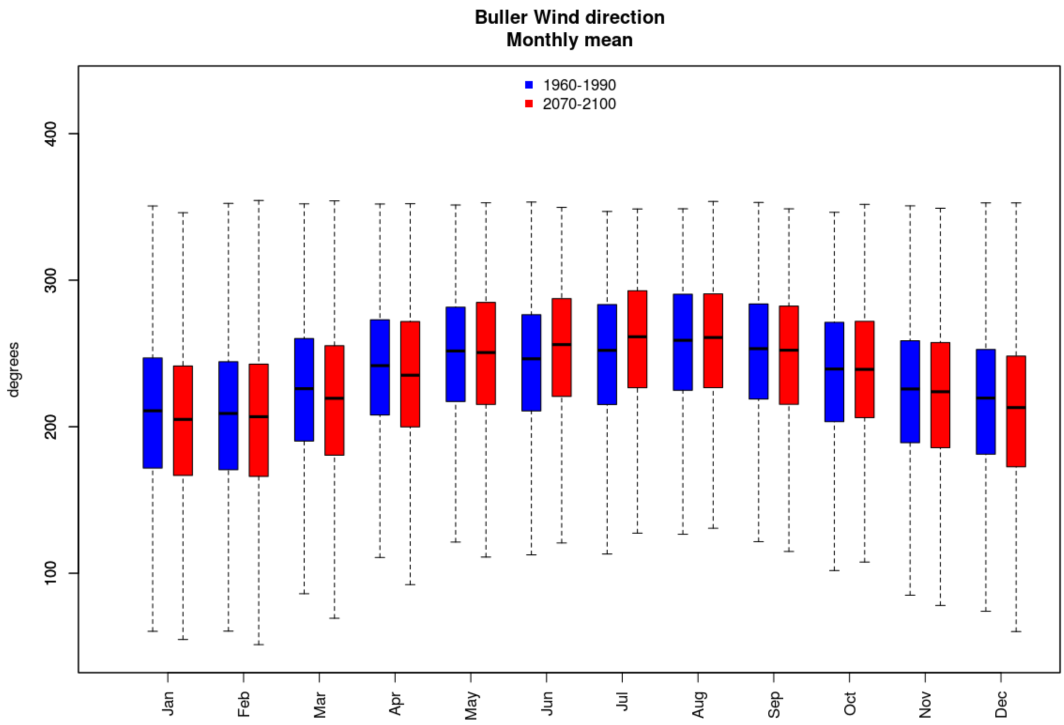

Buller Temperature
Monthly mean
1960-1990
2070-2100
degrees celsius
0
10
20
30
40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Buller Wet Bulb Temperature
Monthly mean
1960-1990
2070-2100
degrees celsius
0
5
10
15
20
25
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Buller Total Precipitation (daily)
Monthly mean
1960-1990
2070-2100
mm
0
5
10
15
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Buller Snowfall (per day)
Monthly mean
1960-1990
2070-2100
mm
0.0
0.5
1.0
1.5
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Buller Wind speed
Monthly mean
1960-1990
2070-2100
m/s
1
2
3
4
5
6
7
8
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Buller Wind direction
Monthly mean
1960-1990
2070-2100
degrees
100
200
300
400
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

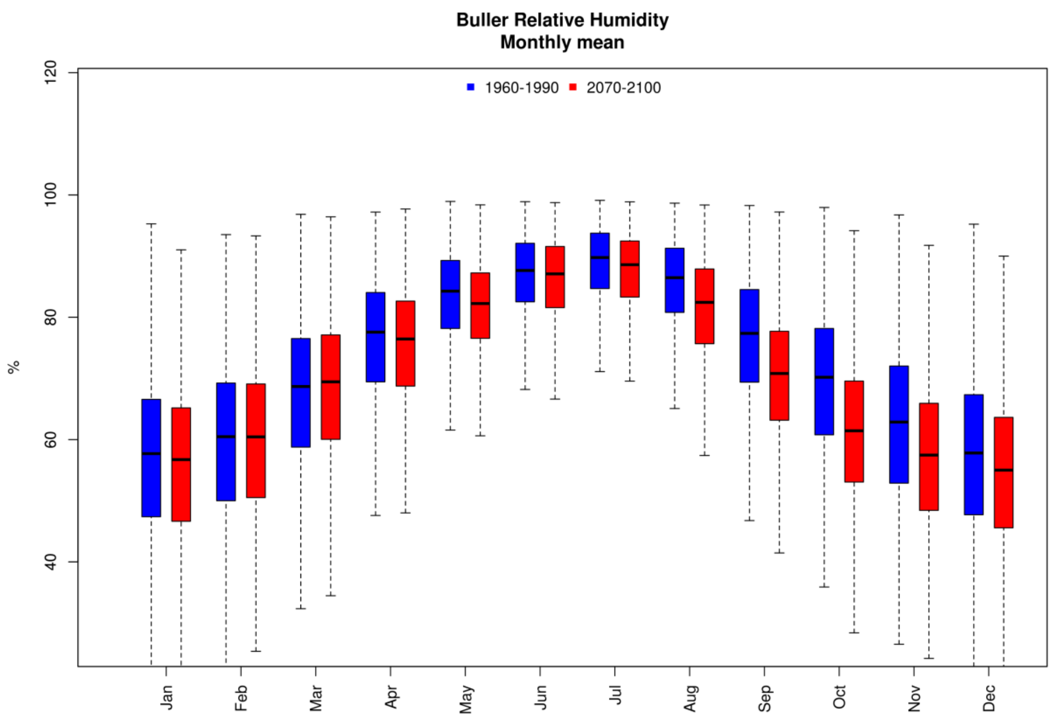


Figure 4.4B: The multi-model monthly mean values of key climate variables in the current (blue) and future (red) time periods. The bottom and top of the box are the 25th and 75th percentiles, the bar is the median, and the whiskers go to the most extreme data point which is no more than +/- 1.5 times the interquartile range from the box. Note that snowfall is the amount of snowfall on days when it snows.

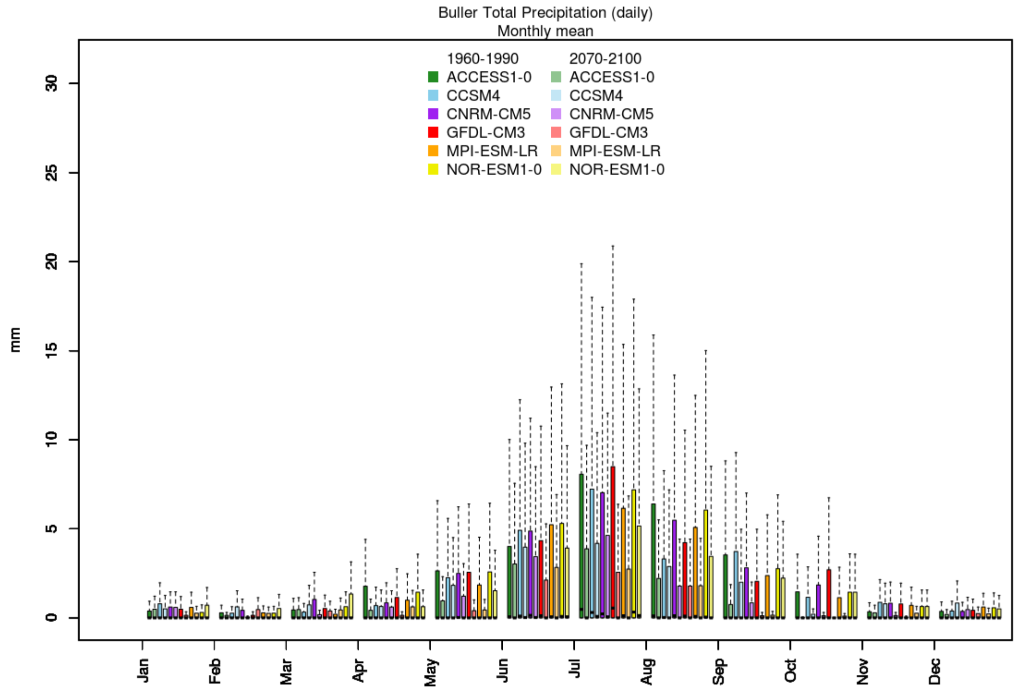


Figure 4.5B: The range in monthly mean precipitation projected by the six climate models in the current and future time periods.

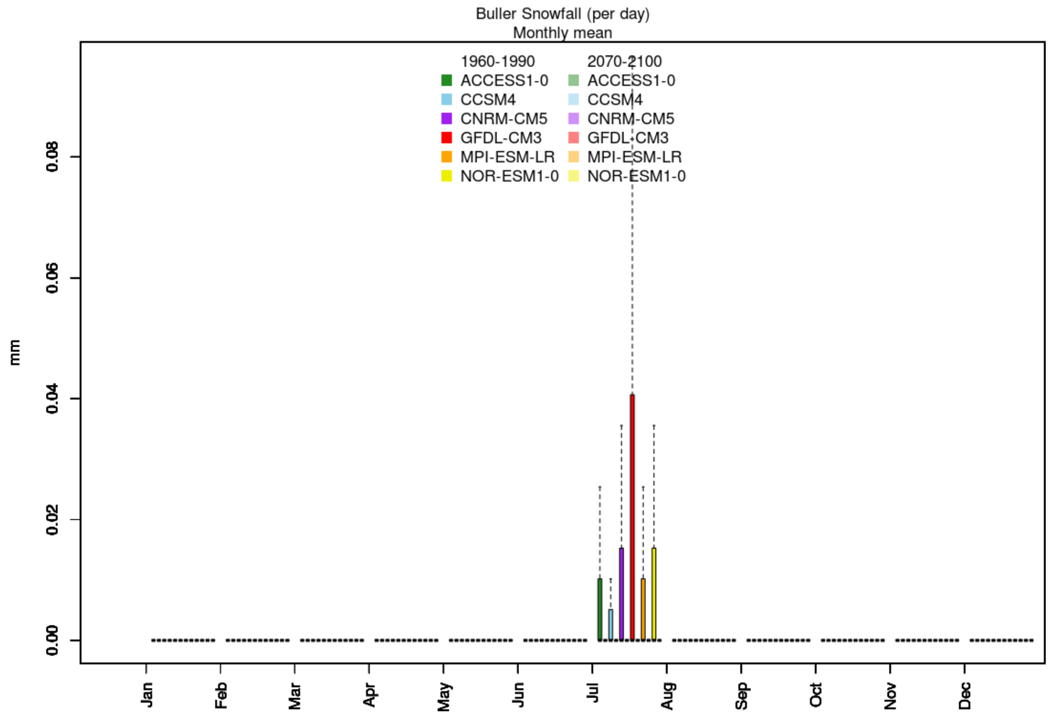


Figure 4.6B: The range in monthly mean snowfall projected by the six climate models in the current and future time periods.

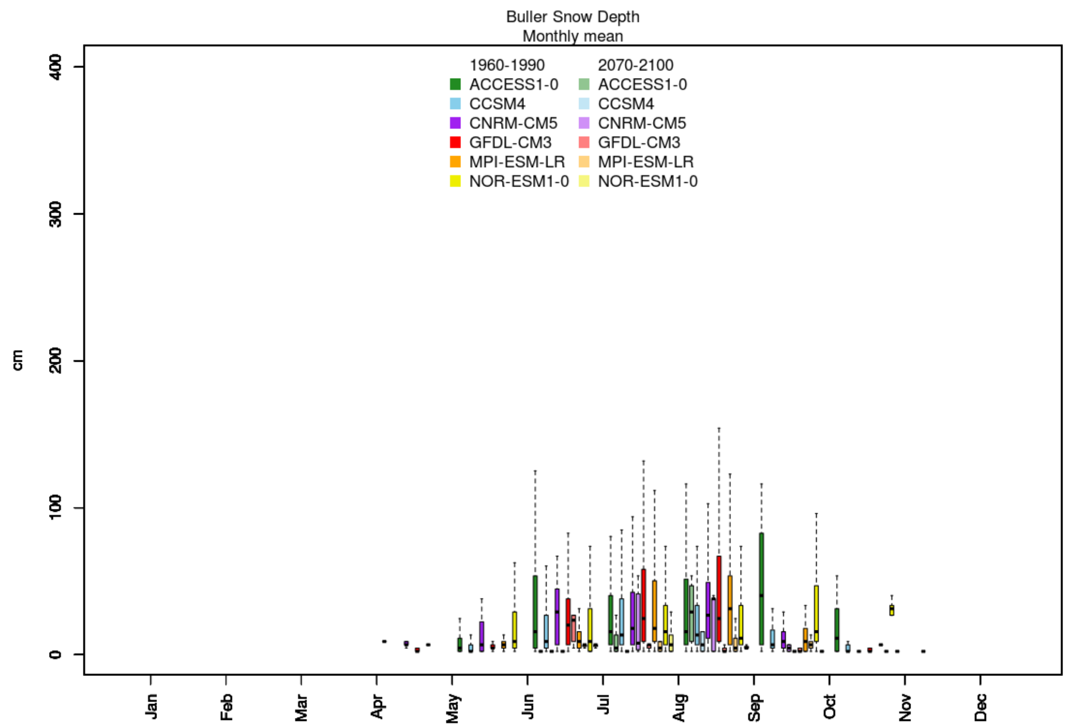


Figure 4.7B: The range in monthly mean snow depth projected by the six climate models in the current and future time periods.

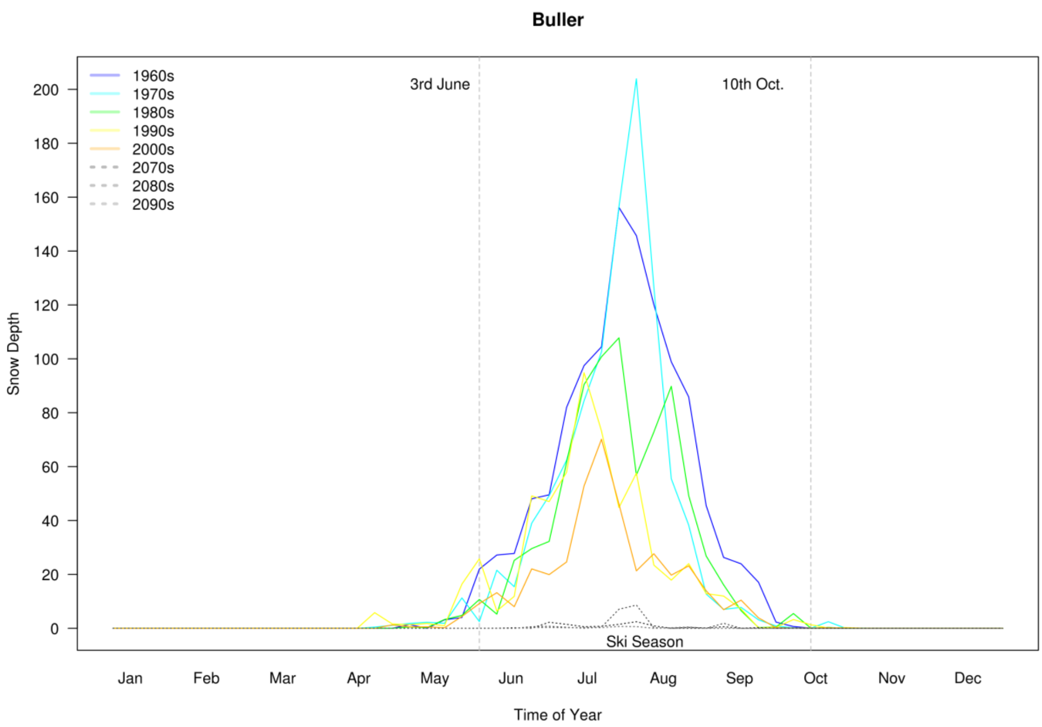


Figure 4.8B: The change in the ski season between current and future periods based on natural snow depth.

Table 4.2B: The number of snowmaking hours that accumulate at Mt Buller by June 3rd based on three different thresholds for wet bulb temperatures (-2°C, -1°C, 0.5°C). Numbers in brackets show the range across the climate models. Values for the decades 1960-2010 and 2070-2090 are based on 3 hourly model output while the decades 2020-2060 are statistically derived.

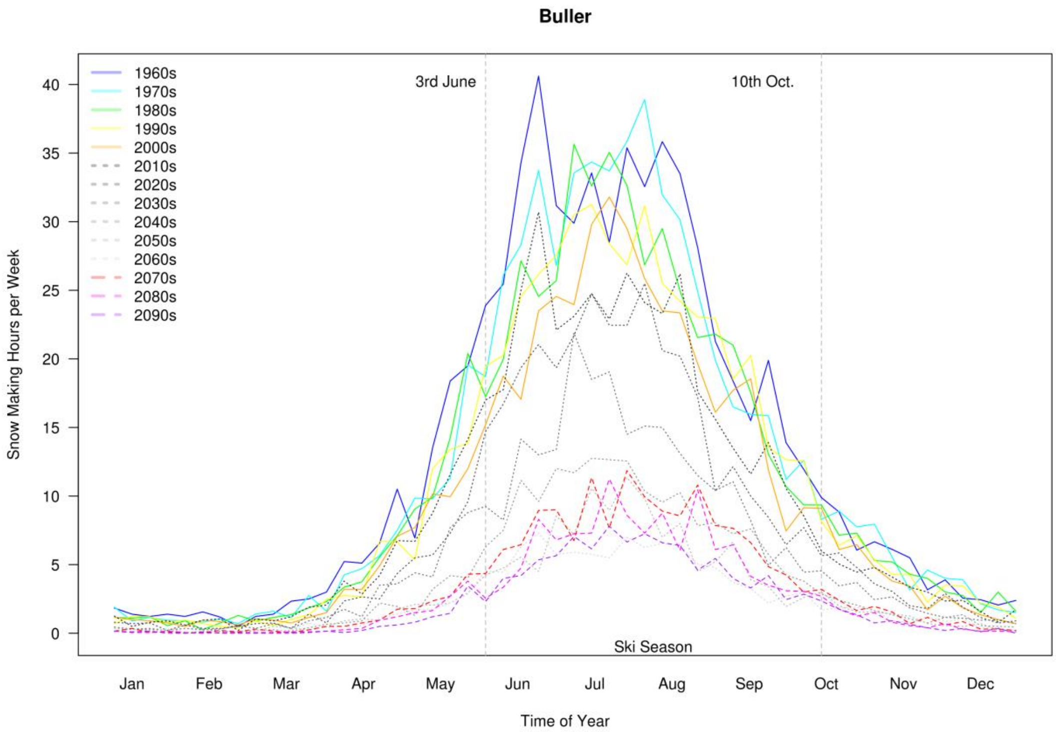
Decade	**Number of hours above Wet Bulb temperature threshold**		
	-2°C	**-1°C**	**0.5°C**
1960s	130 (107 to 160)	217 (188 to 256)	130 (107 to 160)
1970s	108 (100 to 120)	188 (177 to 204)	108 (100 to 120)
1980s	105 (97 to 112)	180 (164 to 190)	105 (97 to 112)
1990s	96 (69 to 118)	168 (126 to 195)	96 (69 to 118)
2000s	85 (70 to 104)	151 (124 to 178)	85 (70 to 104)
2010s	89 (70 to 109)	159 (132 to 183)	89 (70 to 109)
2020s	63 (50 to 75)	119 (106 to 131)	63 (50 to 75)
2030s	50 (41 to 56)	94 (77 to 107)	50 (41 to 56)
2040s	28 (20 to 46)	55 (41 to 78)	28 (20 to 46)
2050s	21 (14 to 26)	44 (35 to 55)	21 (14 to 26)
2060s	19 (13 to 25)	42 (32 to 50)	19 (13 to 25)
2070s	22 (16 to 26)	43 (36 to 50)	22 (16 to 26)
2080s	16 (10 to 24)	36 (25 to 55)	16 (10 to 24)
2090s	11 (5 to 22)	27 (19 to 42)	11 (5 to 22)

Table 4.3B: Shift in ski season start date at Mt Buller for three different thresholds for wet bulb temperatures (-2°C, -1°C, 0.5°C). Numbers in brackets show the range across the climate models. Values for the decades 1960-2010 and 2070-2090 are based on 3 hourly model output while the decades 2020-2060 are statistically derived. NA indicates that the season start date shifts to after the end of the current season (10th October).

Decade	**Shift in season start date relative to the 1960's (Days)**		
	-2°C	**-1°C**	**0.5°C**
1970s	0 (0 to 0)	0 (0 to 0)	0 (0 to 0)
1980s	5 (1 to 10)	5 (2 to 9)	4 (0 to 8)
1990s	8 (5 to 14)	7 (7 to 10)	8 (6 to 10)
2000s	11 (10 to 12)	10 (11 to 12)	11 (9 to 14)
2010s	16 (14 to 19)	15 (14 to 17)	14 (12 to 14)
2020s	13 (13 to 16)	12 (12 to 14)	11 (8 to 14)
2030s	25 (24 to 28)	23 (22 to 26)	21 (20 to 23)
2040s	38 (38 to 43)	36 (43 to 36)	33 (34 to 35)
2050s	64 (75 to 48)	60 (75 to 50)	51 (60 to 50)
2060s	110 (92 to NA)	88 (77 to 102)	69 (64 to 77)
2070s	NA (NA to 155)	124 (NA to 90)	82 (94 to 67)
2080s	86 (91 to 75)	77 (87 to 73)	64 (64 to 62)
2090s	121 (NA to 96)	88 (115 to 76)	70 (81 to 62)

Part II. Climate change in the Australian Alps.
MT BULLER

a)



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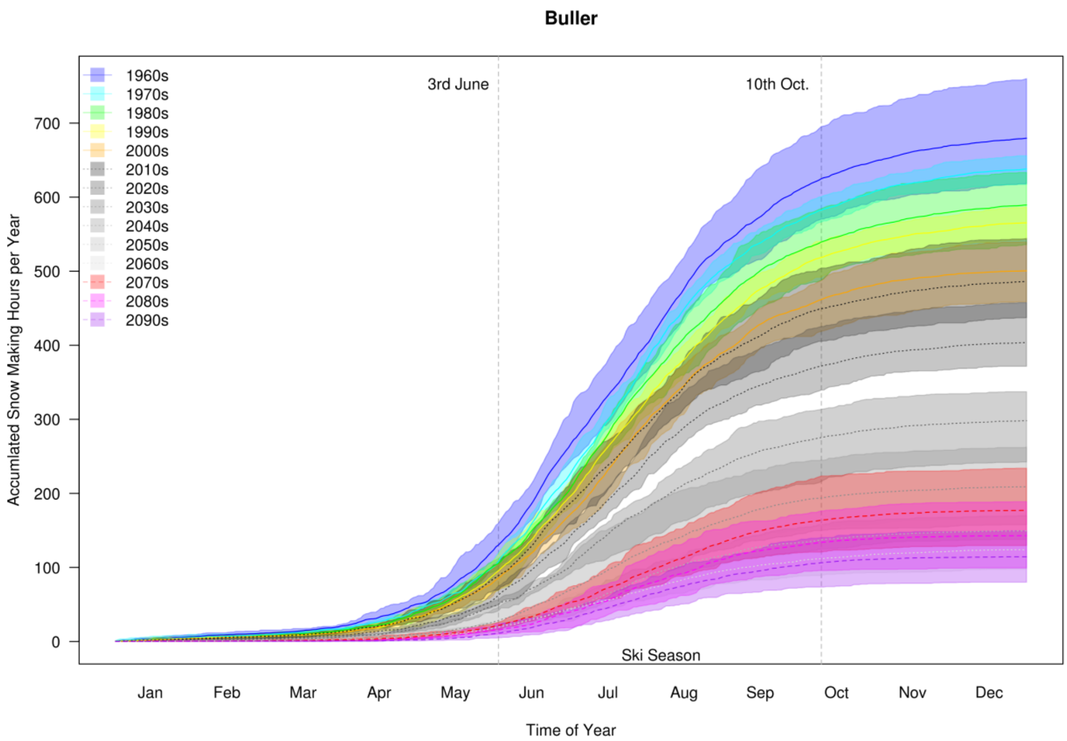
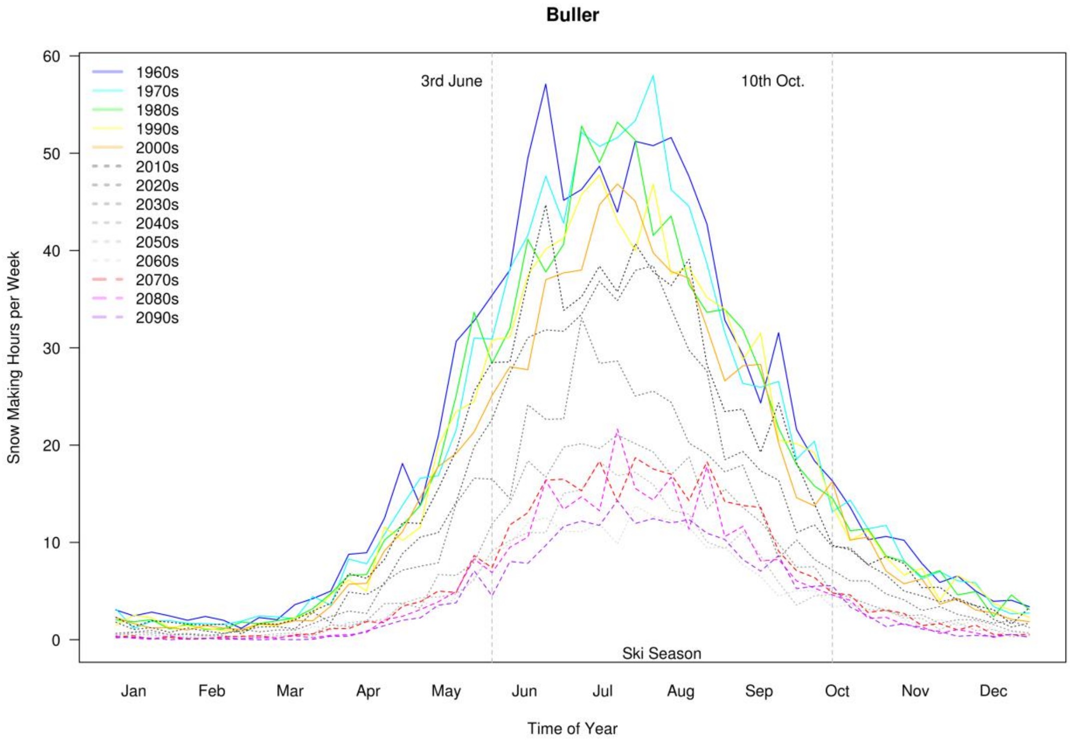


Figure 4.9B: The change in the number of hours suitable for snowmaking between current and future periods based on a threshold of -2°C wet bulb temperature. a) The number of hours per week below the threshold, b) Accumulated snowmaking hours per year

a)



b)

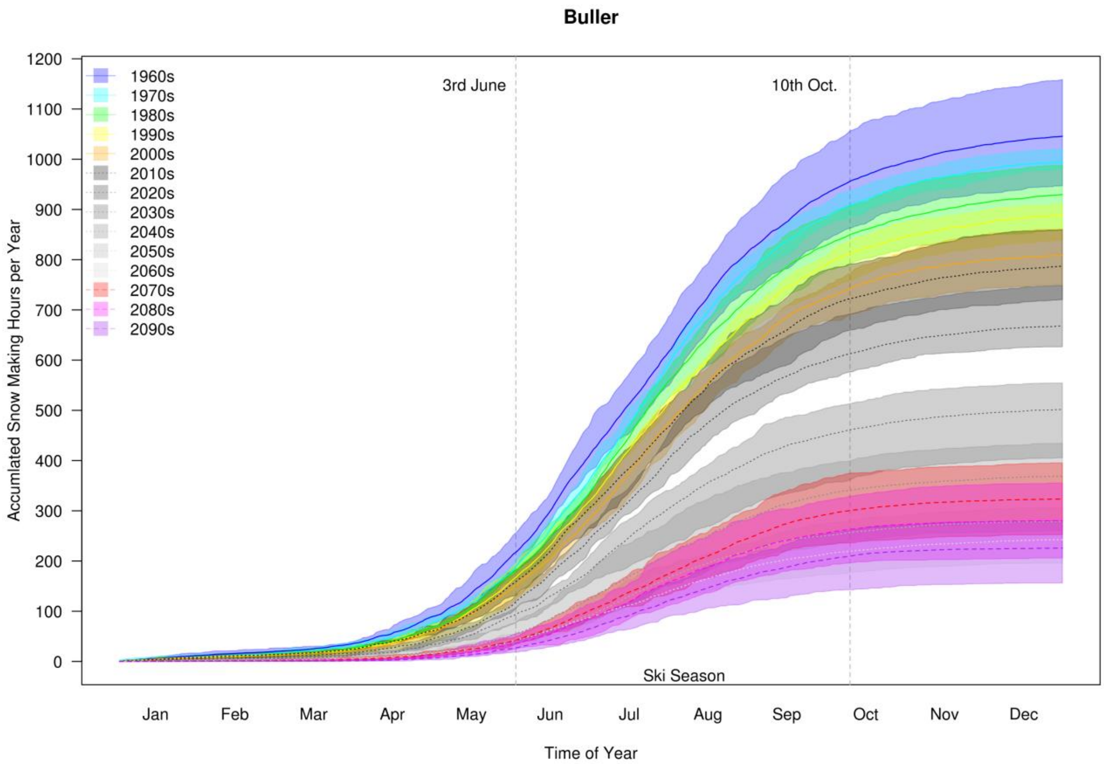
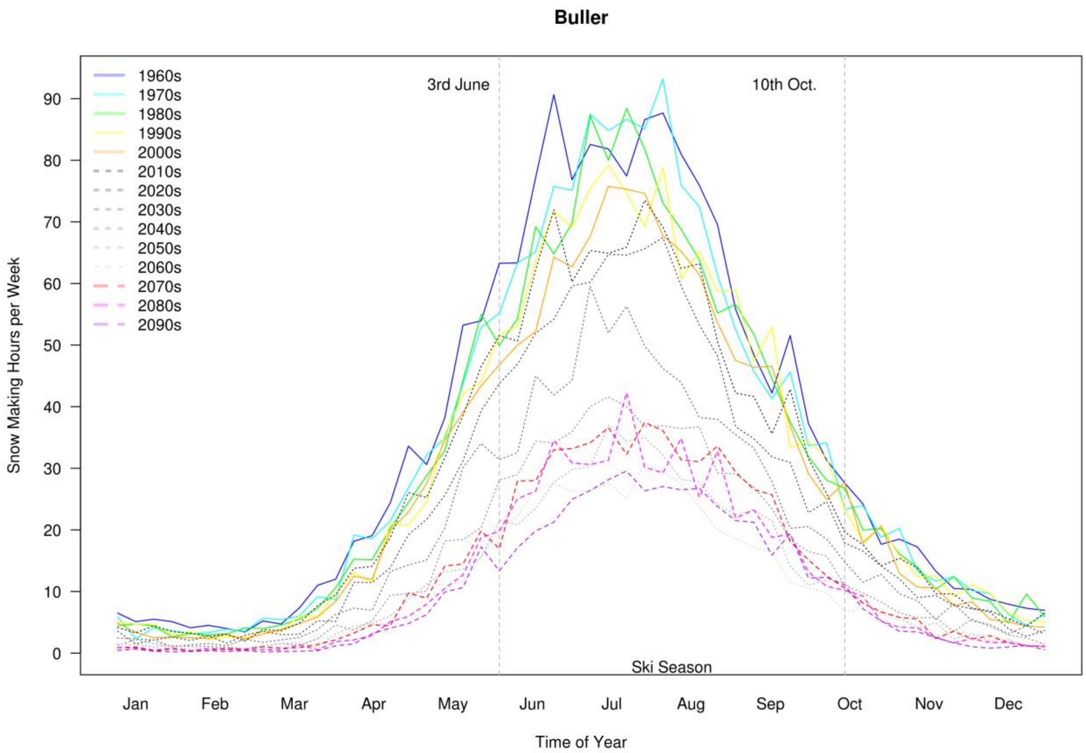


Figure 4.10B: The change in the number of hours suitable for snowmaking between current and future periods based on a threshold of -1°C wet bulb temperature. a) The number of hours per week below the threshold, b) Accumulated snowmaking hours per year

a)



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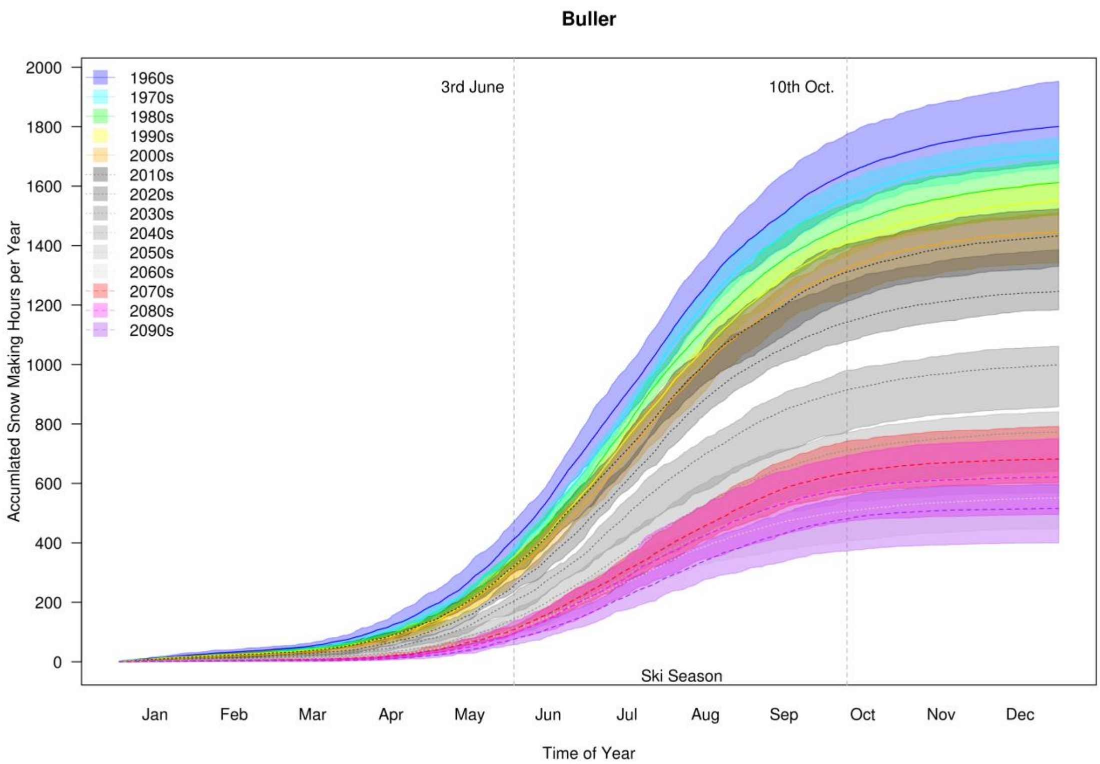


Figure 4.11B: The change in the number of hours suitable for snowmaking between current and future periods based on a threshold of 0.5°C wet bulb temperature. a) The number of hours per week below the threshold, b) Accumulated snowmaking hours per year

C. FALLS CREEK (elevation 1849m)

This section describes the changes in climate that are projected to occur at the Falls Creek resort. An explanation of the Climate Futures for the Australian Alps projections, the methods used and results from across all of the Victorian Alpine resorts can be found in the main report. The main report also provides important information about the scope of the study and considers the uncertainty associated with projections of future climate.

Relative to recent decades (1961-2010), the projections for Falls Creek by the end of the century, under a high emissions scenario, show:

1. An increase in mean annual temperature of 3.5-5.7°C (mean of 4.5°C);
2. An increase in the number of extreme hot temperatures and a decrease in the number of very cold days;
3. The temperature of the coldest days in winter increases by approximately 7°C, while the temperature of the hottest summer days increase by approximately 5°C;
4. A mean decrease in annual precipitation of 14%. However, a maximum decrease of 23% to no change in precipitation is shown across the six climate models;
5. A decrease in precipitation from May through to October for all climate models;
6. Substantial reductions in snowfall, from 85% to 72% less snowfall than the baseline period (mean reduction of 80%);
7. With warmer temperatures there is a reduction in the proportion of precipitation falling as snow. More snow falling as sleet has implications for the retention of snow;
8. No change in wind speed or wind direction.

C1 Changes between current and future periods

The changes projected to occur at Falls Creek between the current (1961-2010) and future (2070-2099) time periods are shown in Table 4.1C.

Figure 4.1C shows the frequency distribution for key climate variables in the modelled current (1961-2010) and future (2069-2099) time periods. The number of occurrences of a particular value is used to highlight any shifts in the overall distribution, the mean or the variance (spread) of the values for each climate variable. There is a shift towards higher temperatures across the distribution, and the shape of the distribution of temperatures (wet and dry bulb) becomes more even, as the peak cold temperatures are lost. There is an increase in the number of extreme hot temperatures and a decrease in the number of very cold days.

The daily values across all models are shown in Figure 4.2C.

The proportion of precipitation falling as snow in the historical, current and future periods are shown in Figure 4.3C. Fewer snow days in the future means that there will be fewer days when precipitation is 100% snow. There is also a reduction in the proportion of snow, with more snow falling as sleet. This has implications for the retention of natural or artificial snow.

C2 Changes to monthly mean values

A comparison of the multi-model mean monthly values of key climate variables in the current and future time periods is presented in Figure 4.4C. Increases in temperature are evident in every month of the year. In the future, the monthly mean temperature of the winter months, (June, July and August) is projected to be more like that currently experienced in autumn and spring. Temperatures in June, July and August in the future are projected to be similar to those currently experienced in April/May or September. May and September in the future period show temperatures similar to those currently experienced in April or October. This could potentially affect the ability for artificial snow to be laid down in the months leading up to the ski season.

Similarly, mean monthly wet bulb temperatures increase in all months, and show the same shifts in winter towards temperatures currently more typical of autumn and spring. Wet bulb temperature does not increase as much as dry bulb temperature, however, because wet bulb temperature reflects the influence of humidity. Note that this summary of monthly values does not show the very low temperatures because it is based on daily means. More detailed analyses of the number of hours per day suitable for snowmaking at particular threshold temperatures are provided in Section C4.

There are no changes to wind speed or direction in any month of the year. Projections of humidity, however, which showed no change in annual means, is projected to decrease slightly from April to August, with more substantial reductions evident in September, October and November (Figure 4.4C).

The large range in monthly values for precipitation are due to the range in values across the six climate models (Table 4.1C). However, all models project decreased precipitation to occur during the months April through to September (Figure 4.5C). In the other months, there is more inconsistency in the direction of change, with some models showing slight increases and others decreases. Substantial reductions in snowfall and snow depth are projected by all climate models in all months (Figure 4.6C, Figure 4.7C). Not only are there fewer days when it snows, but there is reduced snowfall on days when it does snow.

C3 Shifts in the timing and duration of the ski season based on natural snow

The change in the duration and timing of the ski season between current and future periods based on natural snow depth is shown in Figure 4.8C.

All models agrees with observational records that indicate a steady reduction in snow depth over recent decades, from the 1960’s to 2010’s, and the duration of the ski season has contracted, with a later start and earlier finish. Assuming a depth of 30cm is required for skiing, the season length has contracted by 18% relative to the historical period (1960’s) in the model. Relative to the 2000-2010 period, it is projected to contract by 68% by the 2070’s.

C4 Changes to the frequency of suitable snowmaking conditions

The number of hours suitable for snowmaking (below -2°C) before the start of the ski season (June 3rd) at Falls Creek declines from 355 hours in the 1960s to 61 by the end of the century resulting in less than 18% of the historical (1960s) snowmaking opportunities remaining by the end of the century (Table 4.2C). This represents a drop of approximately 6% per decade, but the decline is as high as 16% in the 2020s, followed by further declines of approximately 12-14% in the next two decades. Opportunities for snowmaking relative to the 2010's are halved by 2040-2050.

If snow is made at warmer temperatures, more hours are available for snowmaking for longer into the future, but still decline to 115 hours below -1°C and 220 hours below 0.5°C by the final decade of the century.

The drop in conditions suitable for snowmaking throughout the year is presented graphically for the three wet bulb temperature thresholds (-2°C, -1°C, 0.5°C) in Figures 4.9C to 4.11C. Values for the decades 1960-2010 and 2070-2090 are based on the multi-model mean of 3 hourly data from the dynamically downscaled model runs, while the decades 2020-2060 are the multi-model mean of 3 hourly data from the statistically derived values (see Box 2 in the main report). The results show a gradual decline from 1960 to 2000, followed by a marked drop in available hours for snowmaking between the 2020's and 2030's. If warmer thresholds are accepted, with the associated trade-offs in cost and quality of snow, the number of hours suitable for making snow is higher than at colder temperatures.

The accumulation of hours below different threshold temperatures can be used to indicate the start of the ski season, and the quality of snow that may be made (Figures 4.9C to 4.11C). In the 1960's, approximately 350 hours below -2°C wet bulb temperature had accumulated, on average, before the ski season start date (3rd June). By 2020 this is projected to decline to 200 hours available for making snow. By 2070, less than 100 hours below -2°C accumulate before 3rd June. We use the 1960s value (350 hours below -2°C) to indicate the climatic beginning of the ski season (rather than the calendar date). In these terms, the changes equate to a relative shift in the start of the ski season from the 3rd June (1960's) to the 24th June in the 2020's and the 7th and 21st July in the 2030's and 2040's. By the end of the century, it would not be until the 15th October that the same number of snowmaking hours would accumulate.

As natural snow declines, more snow will need to be made, under warmer conditions, to achieve the target snow depth profile throughout the season (see Table 2 in the main report). At Falls Creek, by 2070, almost all snow will need to be artificially produced, in approximately 60% fewer snowmaking hours (relative to 2010). However, if snow is made at warmer temperatures, snowmaking hours can be maintained at current (2010) levels until the 2030's (-1°C wet bulb temperature) or the 2080's (-0.5°C). For example, by the start of the season, at present (2010) there are about 40 snowmaking hours below -2°C per week. By 2070 this drops to 15 hours, but if the warmer threshold of 0.5°C is used, 40 hours remain.

Table 4.1C: Projected change in key climate variables at Falls Creek between the current (1961-2010) and future (2070-2099) time periods. The multi-model mean is shown for each 30 year period, with the range in climate models shown in brackets.

	Temperature (°C)			Wet bulb temperature (°C)			Precipitation (mm)		Snowfall (mm)		Wind speed (m/s)	Wind direction (m/s)
	Minimum Winter	Maximum Summer	Mean annual	Minimum Winter	Maximum Summer	Mean annual	Mean Daily	Mean Annual	Maximum weekly	Mean Annual Maximum	Mean annual	
Current	-9.54 (-10.08, -9.14)	22.44 (21.85 , 23.07)	5.60 (5.51 , 5.73)	-22.92 (-30, -20.03)	20 (20, 20)	3.34 (3.24, 3.46)	8.10 (7.85, 8.48)	2956.5	29.04 (24.09, 32.39)	1510.08	4.44 (4.40, 4.47)	250.15 (249.08, 250.98)
Future	-2.33 (-2.96, -1.91)	27.79 (25.37 , 29.73)	10.07 (9.02 , 11.19)	-11.78 (-13.43, -9.85)	24.71 (21.44, 30)	7.17 (6.67, 7.80)	7.00 (6.04, 8.50)	2555	6.04 (3.58, 9.20)	314.08	4.39 (4.30, 4.48)	254.27 (251.12, 257.47)
Change	7.21 (6.64 , 7.98)	5.35 (3.11 , 7.44)	4.47 (3.50, 5.65)	11.14 (8.16, 16.57)	4.71 (1.44, 10)	3.83 (3.39, 4.46)	-1.10 (-2.43, 0.65)	-14% (-23%, 0%)	-23.00 (-28.81, -15.38)	-79% (-85%,-72%)	-0.05 (-0.14, 0.02)	4.12 (1.78, 7.13)

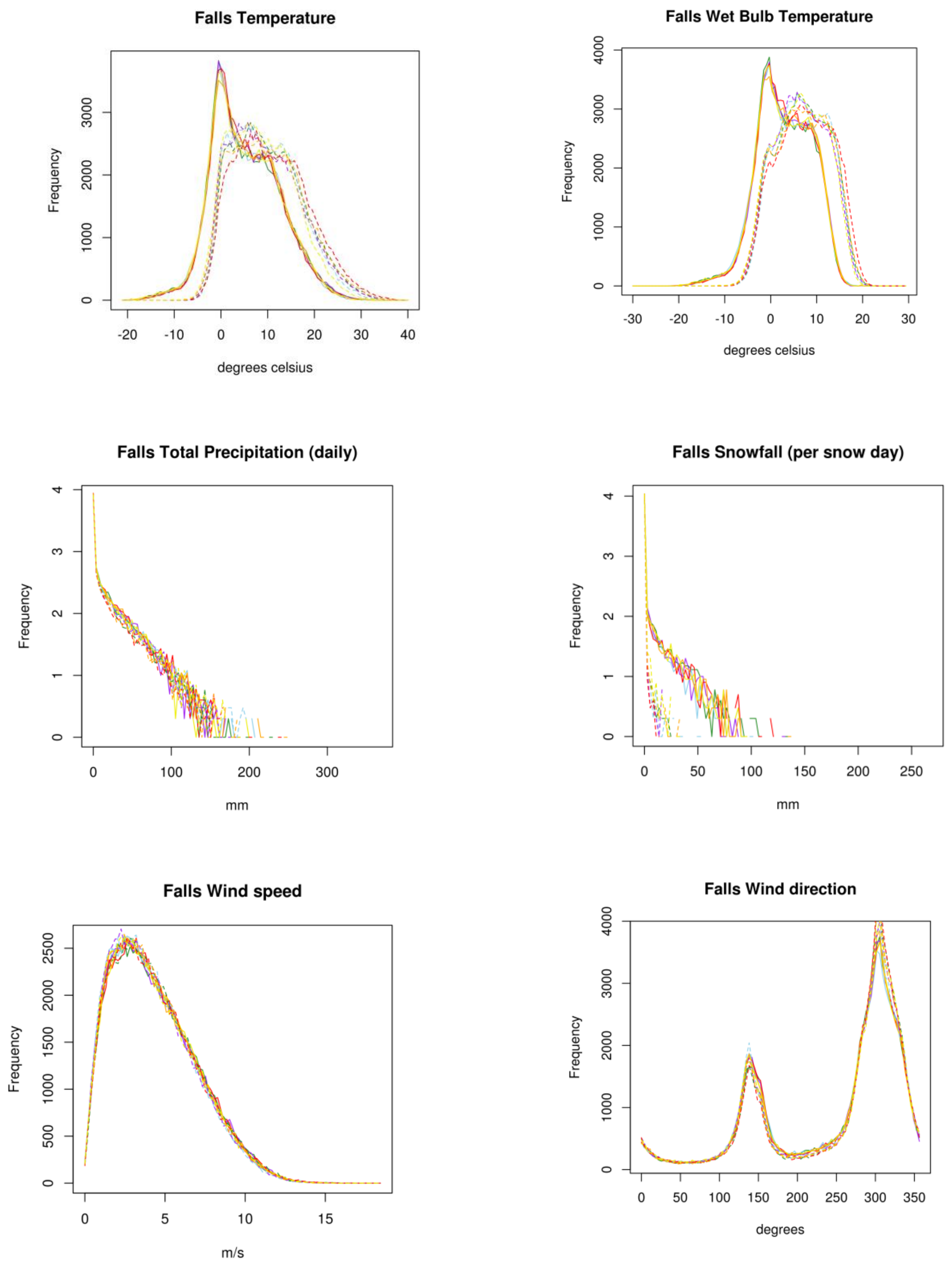


Figure 4.1C: Frequency distribution of key climate variables in the modelled current (full lines) and future (dashed lines) time periods. The six climate models are shown in different colours. log values for daily precipitation and snowfall are shown.

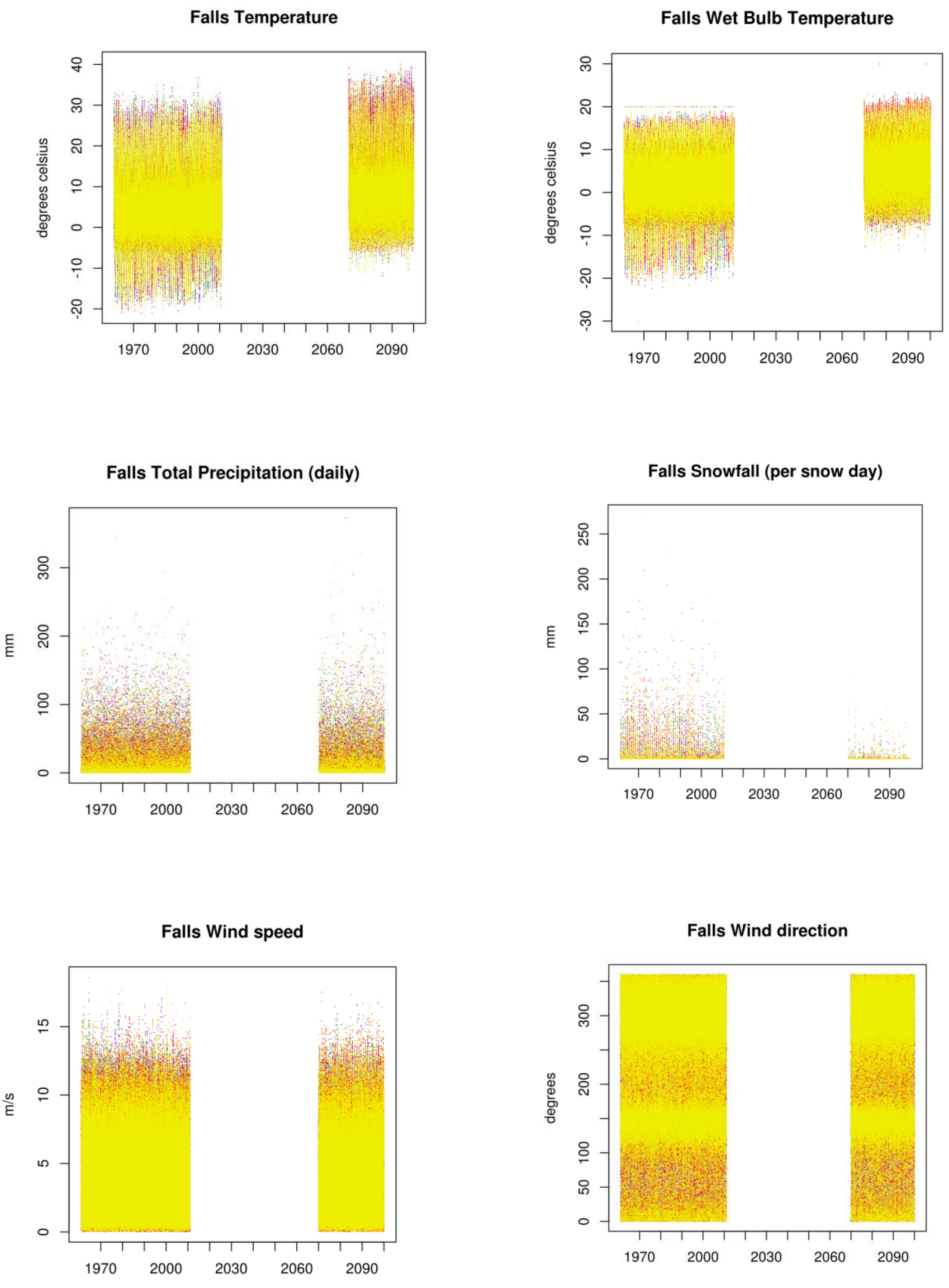


Figure 4.2C: Daily values of key climate variables from the six climate models showing the modelled periods, 1961-2010 and 2070-2099.

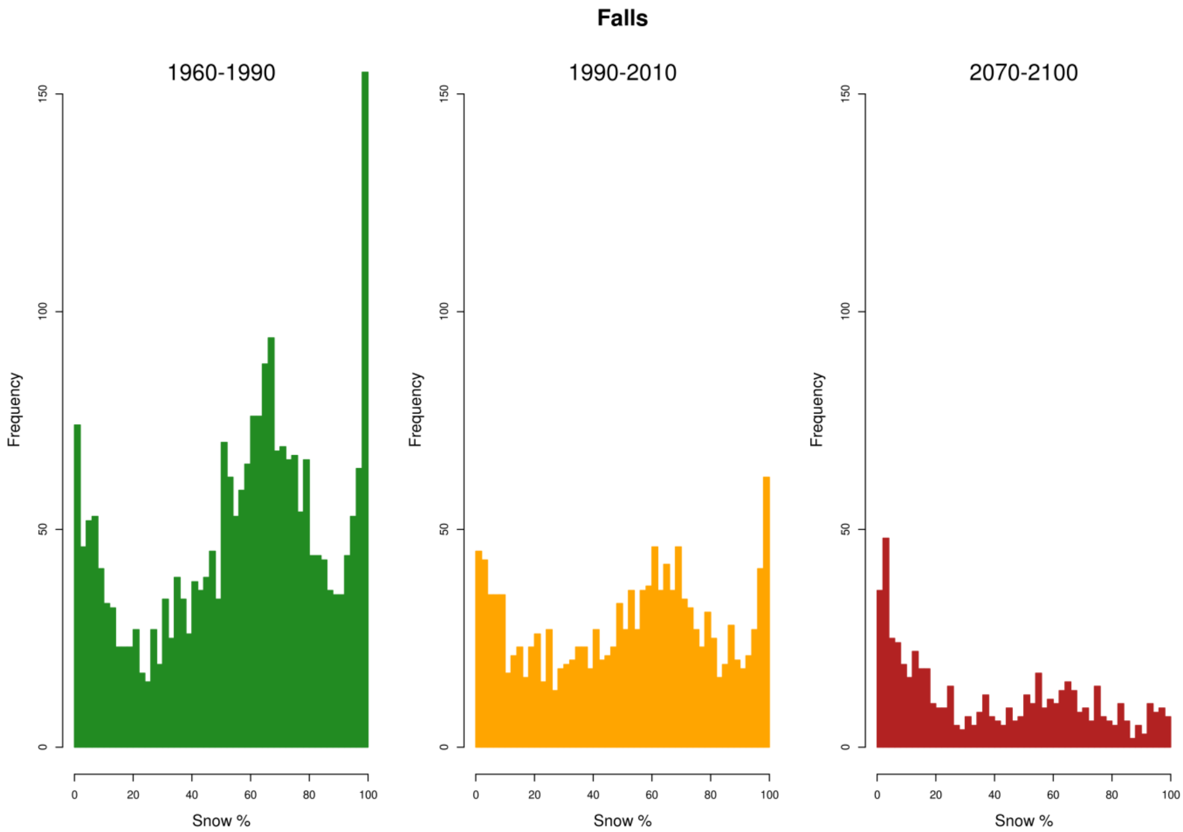
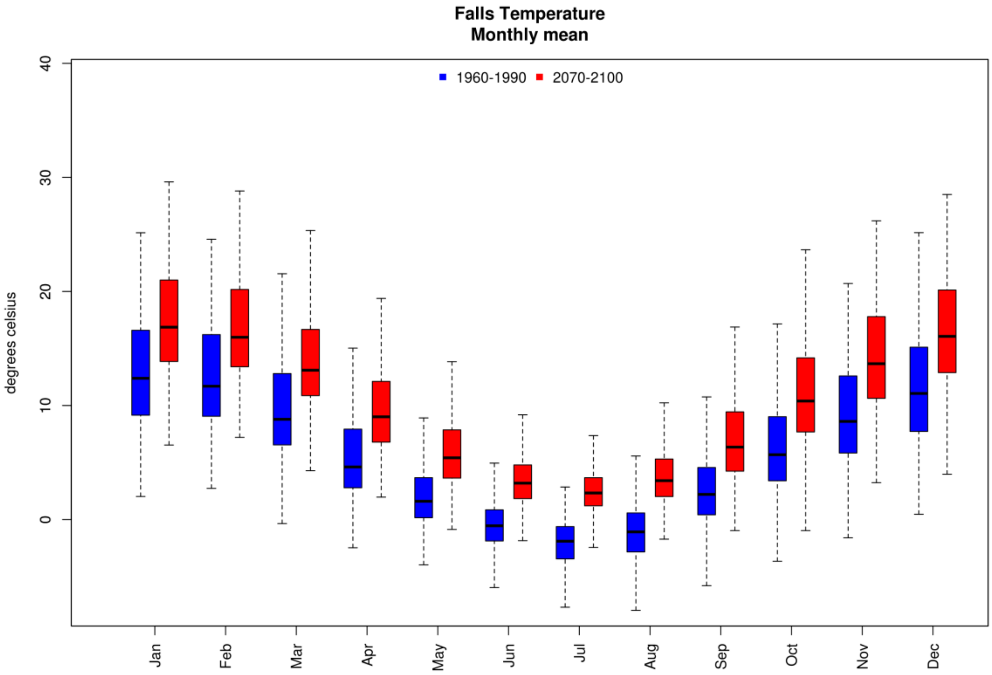
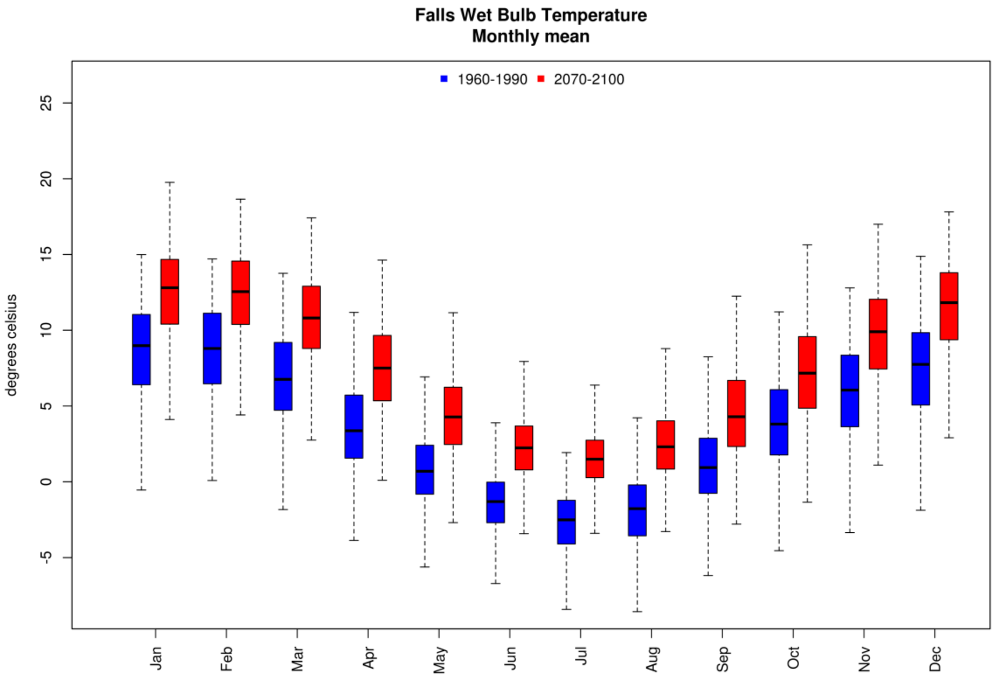
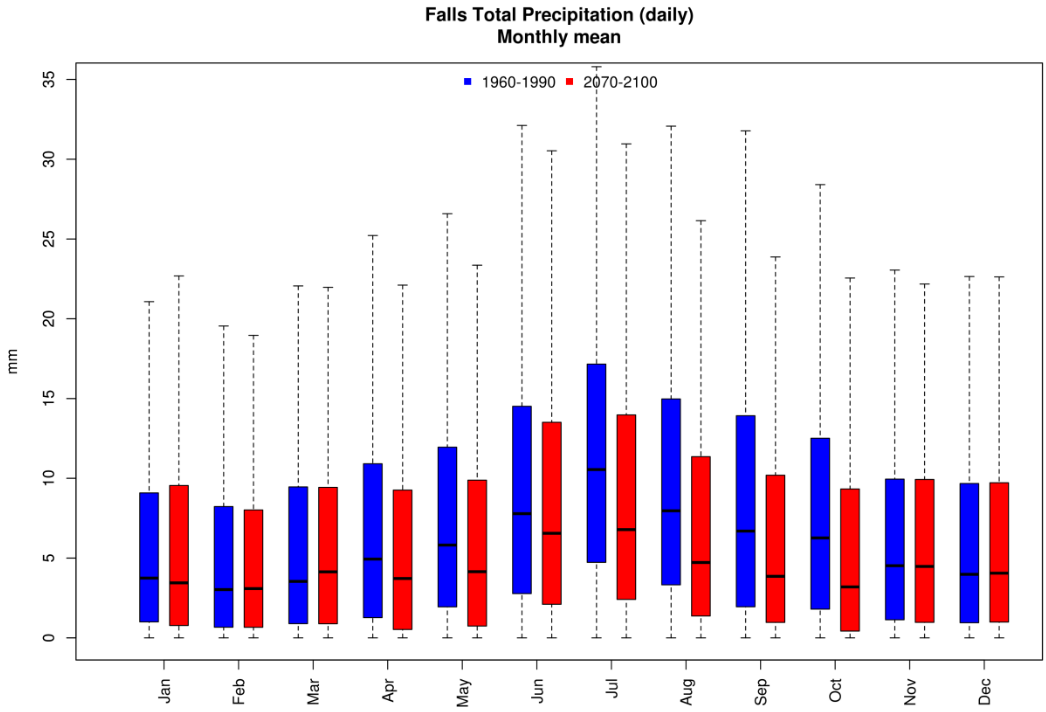
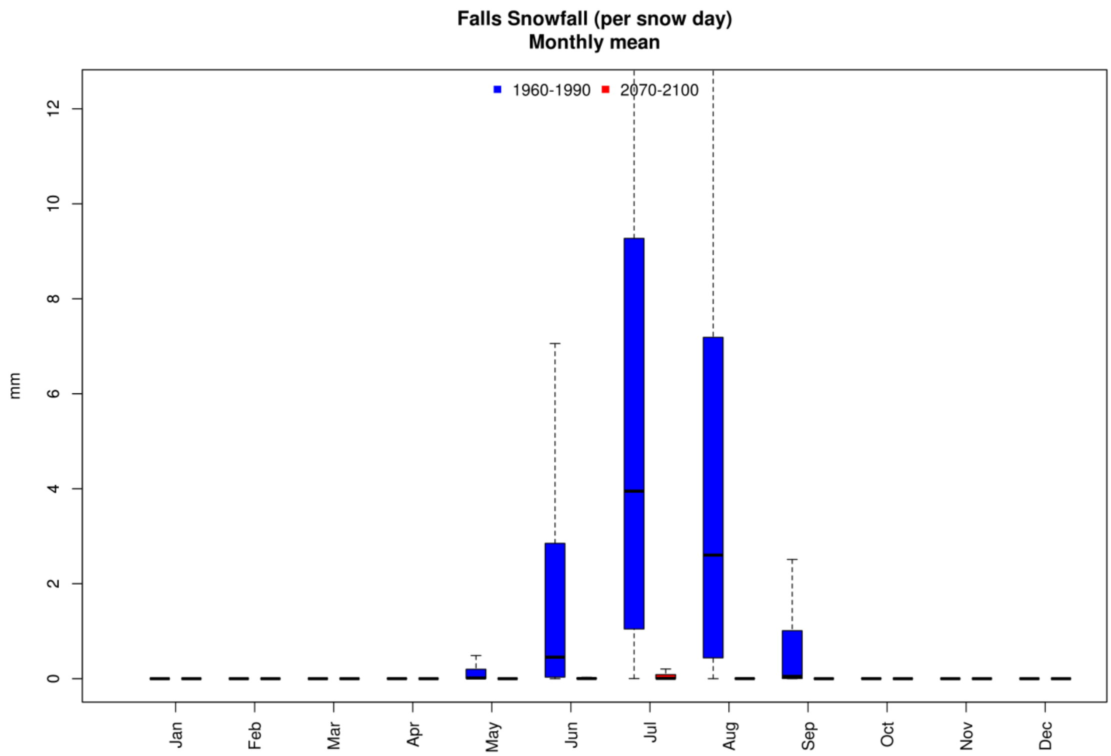


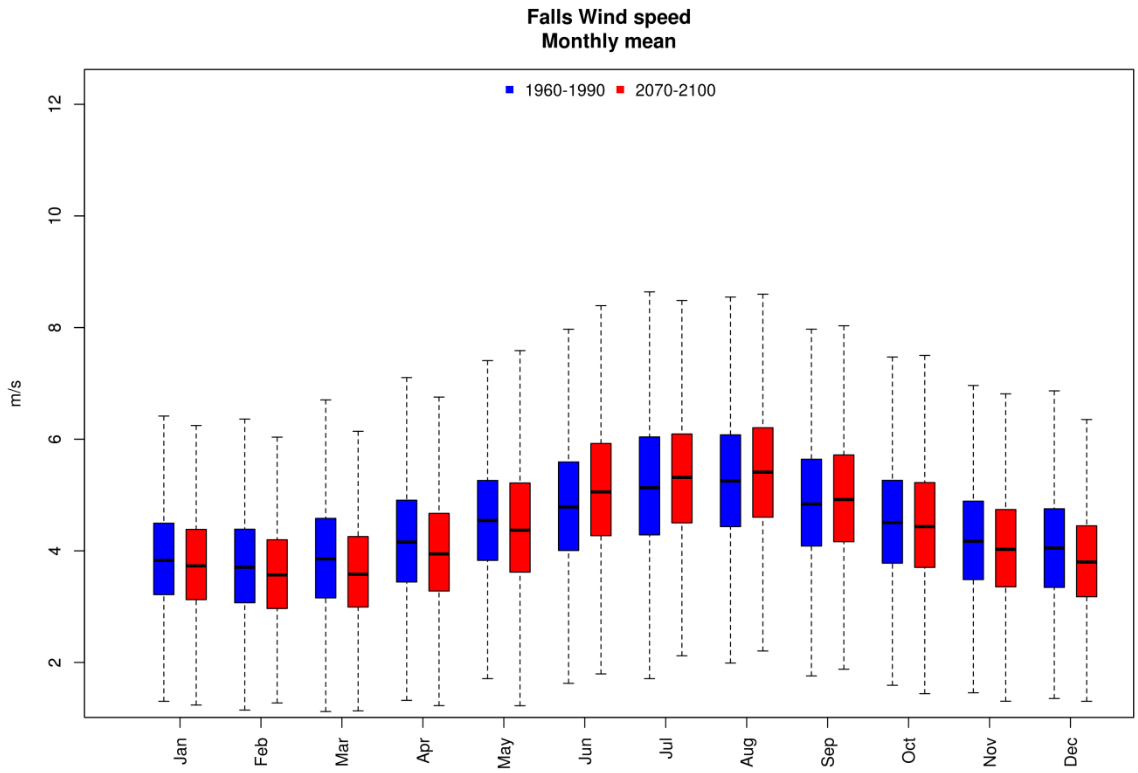
Figure 4.3C: The proportion of precipitation falling as snow in the historical (1960-1990), current (1990-2010) and future (2070-2100) periods.

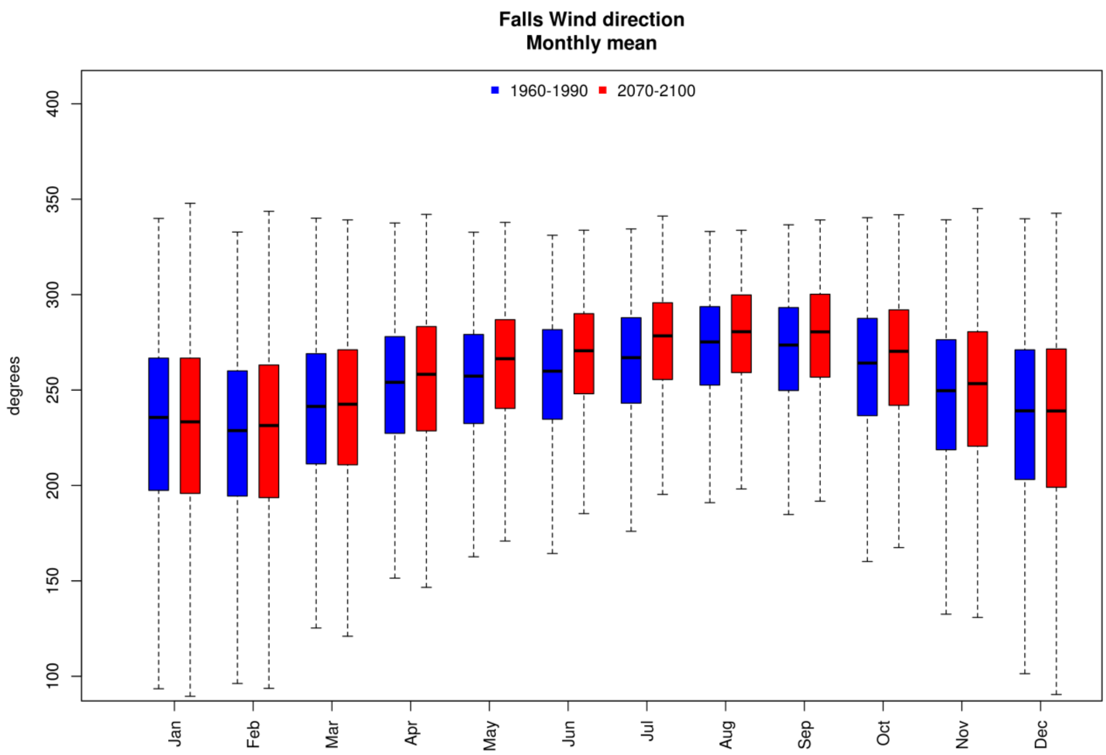

Falls Temperature
Monthly mean
1960-1990
2070-2100
degrees celsius
0
10
20
30
40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Falls Wet Bulb Temperature
Monthly mean
1960-1990
2070-2100
degrees celsius
-5
0
5
10
15
20
25
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Falls Total Precipitation (daily)
Monthly mean
1960-1990
2070-2100
mm
0
5
10
15
20
25
30
35
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Falls Snowfall (per snow day)
Monthly mean
1960-1990
2070-2100
mm
0
2
4
6
8
10
12
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Falls Wind speed
Monthly mean
1960-1990
2070-2100
m/s
2
4
6
8
10
12
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Falls Wind direction
Monthly mean
1960-1990
2070-2100
degrees
100
150
200
250
300
350
400
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

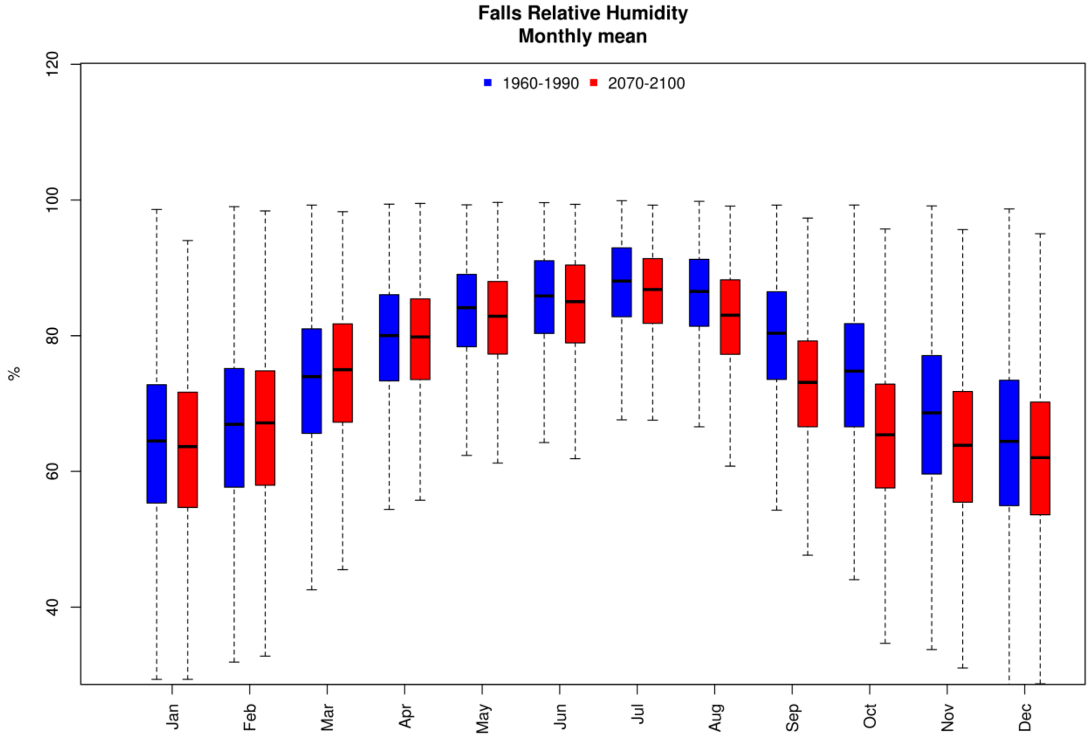


Figure 4.4C: The multi-model monthly mean values of key climate variables in the current (blue) and future (red) time periods. The bottom and top of the box are the 25th and 75th percentiles, the bar is the median, and the whiskers go to the most extreme data point which is no more than +/- 1.5 times the interquartile range from the box. Note that snowfall is the amount of snowfall on days when it snows.

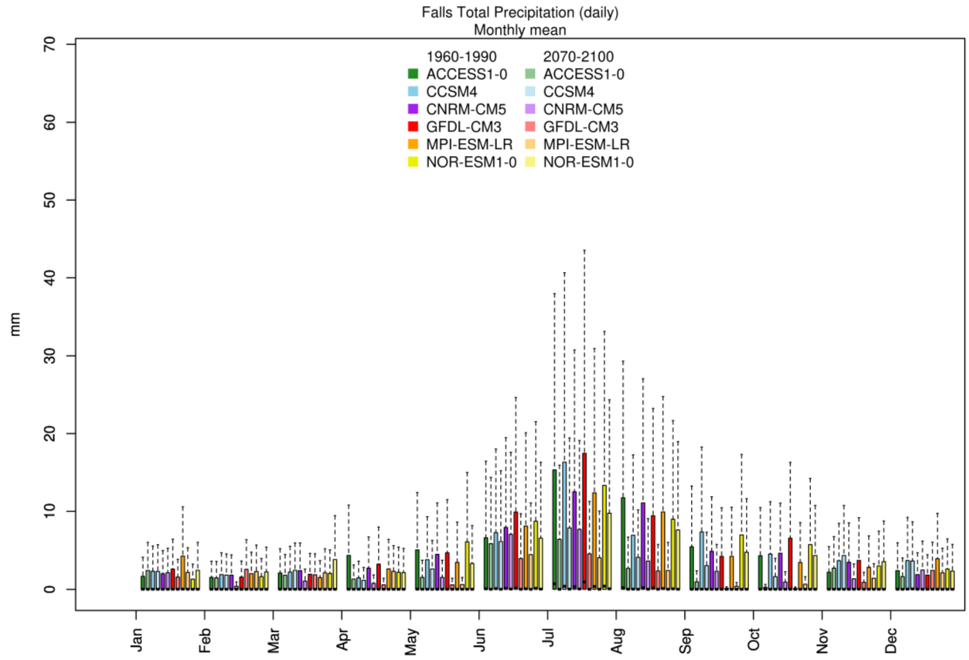


Figure 4.5C: The range in monthly mean precipitation projected by the six climate models in the current and future time periods.

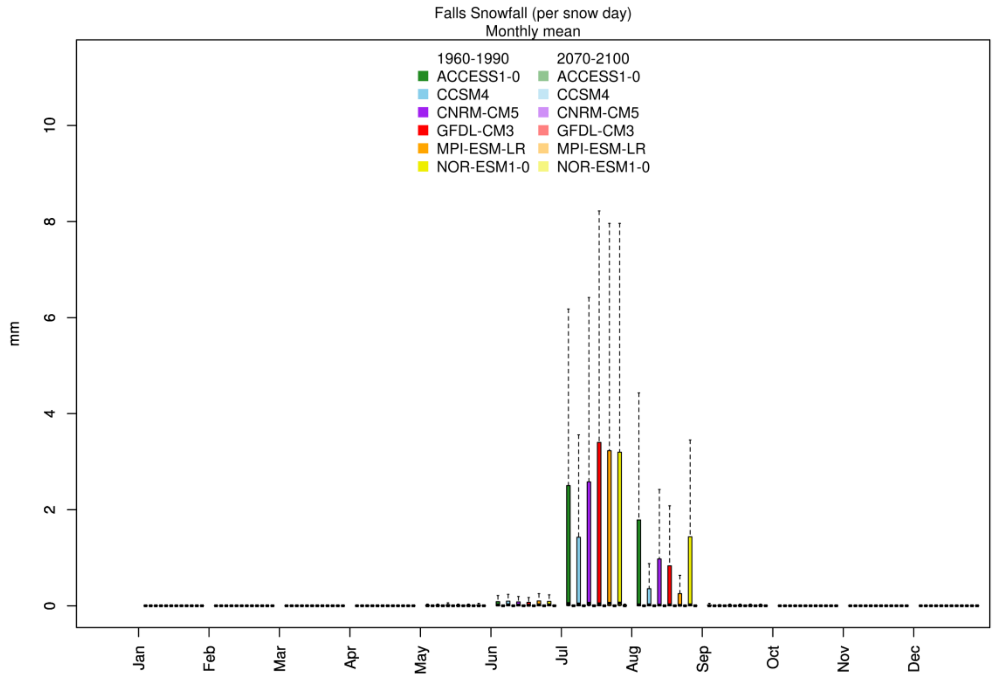


Figure 4.6C: The range in monthly mean snowfall projected by the six climate models in the current and future time periods.

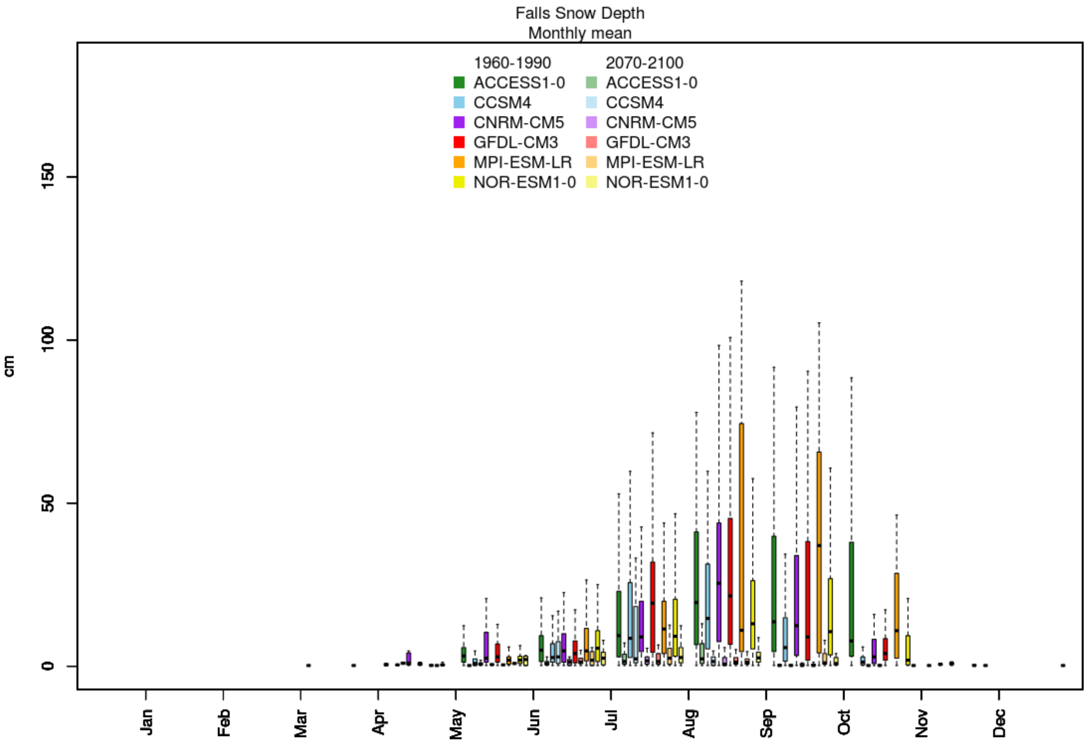


Figure 4.7C: The range in monthly mean snow depth projected by the six climate models in the current and future time periods.

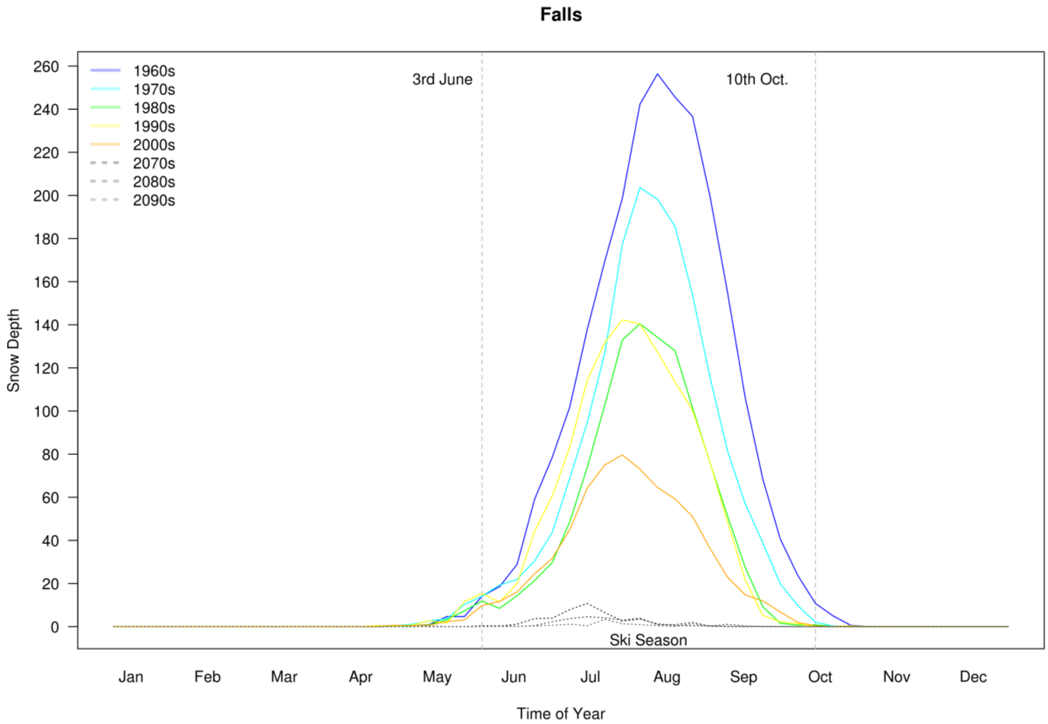


Figure 4.8C: The change in the ski season between current and future periods based on natural snow depth.

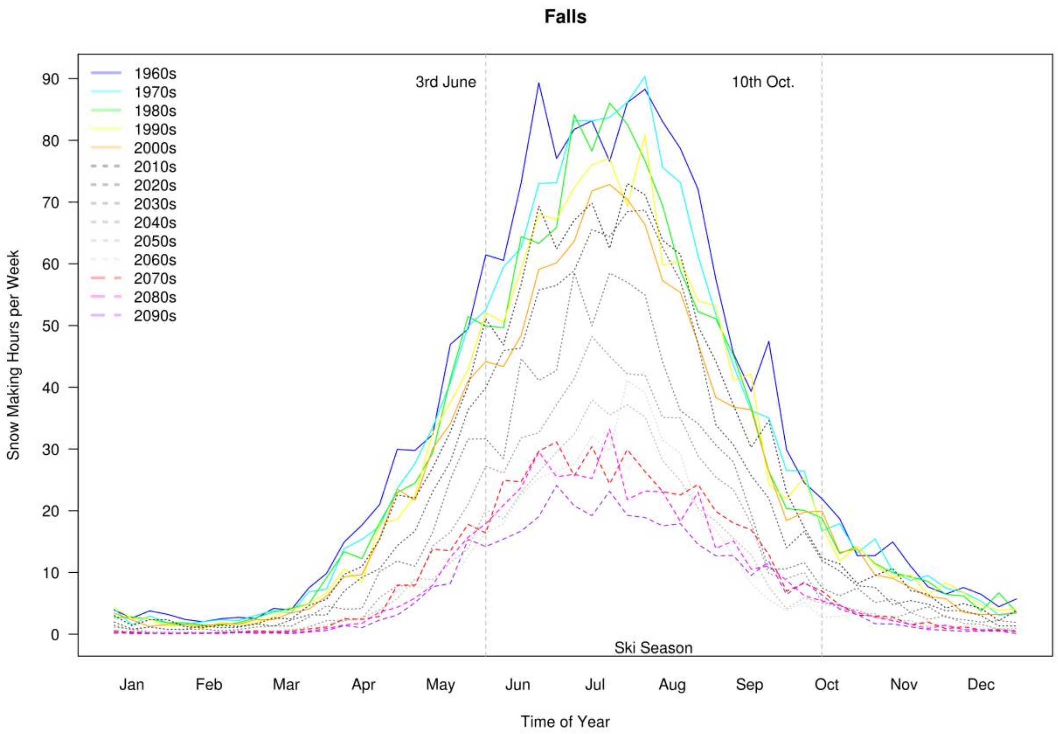
Table 4.2C: The number of snowmaking hours that accumulate at Falls Creek by June 3rd based on three different thresholds for wet bulb temperatures (-2°C, -1°C, 0.5°C). Numbers in brackets show the range across the climate models. Values for the decades 1960-2010 and 2070-2090 are based on 3 hourly model output while the decades 2020-2060 are statistically derived.

Decade	**Number of hours above Wet Bulb temperature threshold**		
	-2°C	**-1°C**	**0.5°C**
1960s	355 (304 to 417)	508 (442 to 584)	775 (701 to 868)
1970s	318 (295 to 331)	462 (433 to 475)	724 (695 to 745)
1980s	304 (277 to 334)	442 (409 to 466)	691 (647 to 742)
1990s	280 (261 to 296)	410 (384 to 426)	647 (609 to 694)
2000s	262 (234 to 291)	388 (340 to 420)	622 (546 to 681)
2010s	263 (236 to 295)	390 (357 to 436)	635 (596 to 688)
2020s	206 (187 to 219)	314 (276 to 329)	540 (494 to 560)
2030s	164 (128 to 182)	255 (212 to 277)	460 (401 to 516)
2040s	114 (94 to 138)	189 (163 to 224)	356 (321 to 401)
2050s	85 (67 to 103)	149 (115 to 183)	298 (261 to 343)
2060s	75 (67 to 92)	136 (118 to 164)	267 (235 to 320)
2070s	91 (82 to 106)	155 (140 to 182)	287 (266 to 333)
2080s	75 (53 to 100)	129 (98 to 162)	248 (201 to 289)
2090s	61 (47 to 85)	115 (84 to 157)	220 (178 to 290)

Table 4.3C: Shift in ski season start date at Falls Creek for three different thresholds for wet bulb temperatures (-2°C, -1°C, 0.5°C). Numbers in brackets show the range across the climate models. Values for the decades 1960-2010 and 2070-2090 are based on 3 hourly model output while the decades 2020-2060 are statistically derived.

Decade	**Shift in season start date relative to the 1960's (Days)**		
	-2°C	**-1°C**	**0.5°C**
1970s	0 (0 to 0)	0 (0 to 0)	0 (0 to 0)
1980s	4 (0 to 9)	4 (0 to 8)	3 (0 to 7)
1990s	7 (5 to 11)	7 (3 to 10)	6 (3 to 8)
2000s	10 (6 to 15)	9 (6 to 15)	8 (6 to 12)
2010s	14 (10 to 16)	13 (11 to 15)	11 (11 to 12)
2020s	12 (9 to 13)	12 (9 to 13)	10 (7 to 11)
2030s	21 (19 to 25)	20 (21 to 24)	17 (18 to 18)
2040s	31 (31 to 32)	31 (30 to 32)	26 (26 to 28)
2050s	45 (48 to 49)	44 (45 to 47)	38 (39 to 38)
2060s	61 (60 to 64)	58 (58 to 62)	50 (50 to 50)
2070s	66 (71 to 59)	59 (63 to 57)	52 (55 to 51)
2080s	67 (66 to 61)	58 (59 to 56)	49 (51 to 49)
2090s	80 (106 to 69)	67 (72 to 59)	56 (60 to 53)

a)



b)

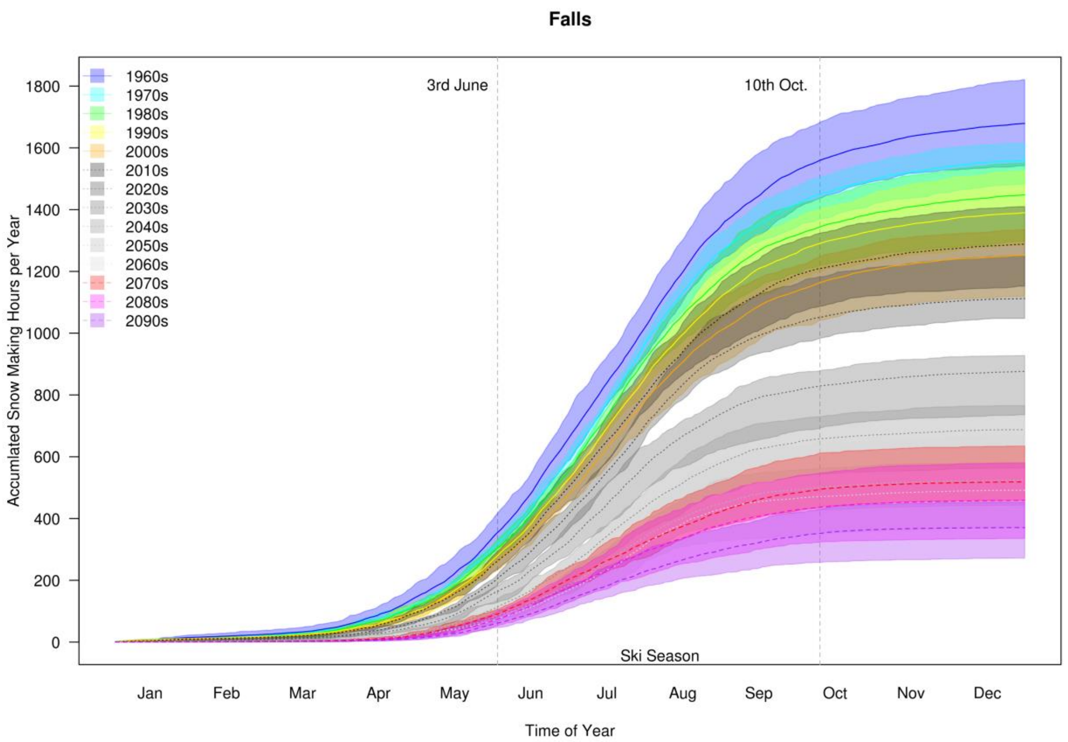
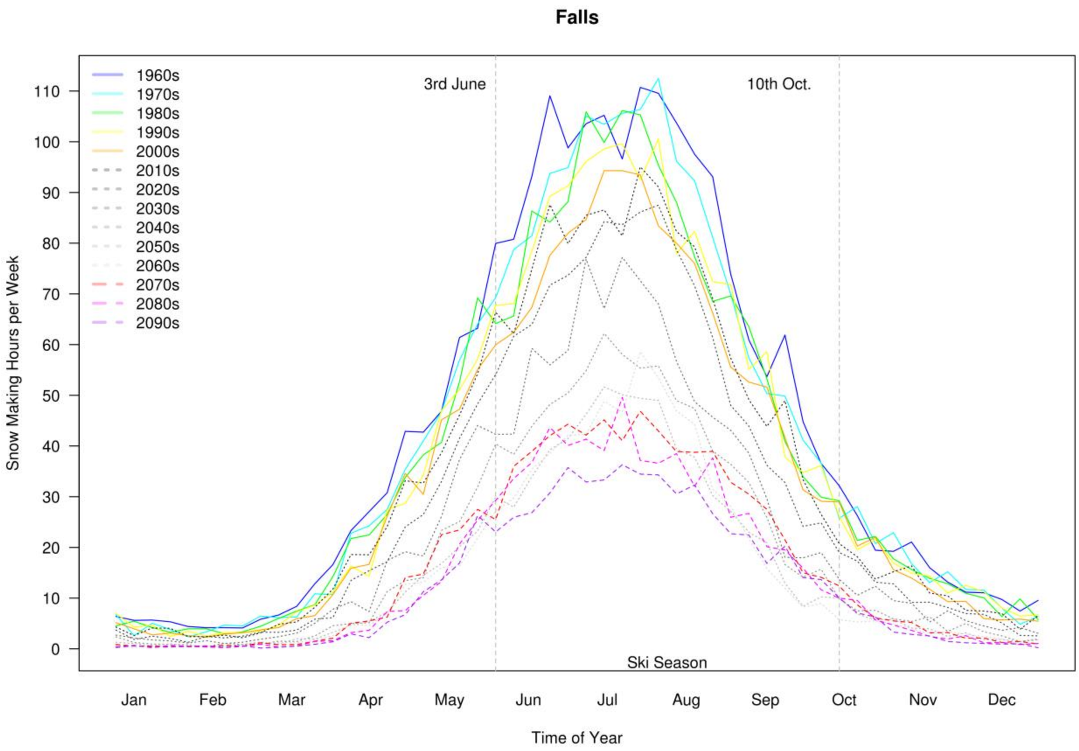


Figure 4.9C: The change in the number of hours suitable for snowmaking between current and future periods based on a threshold of -2°C wet bulb temperature. a) The number of hours per week below the threshold, b) Accumulated snowmaking hours per year

a)



b)

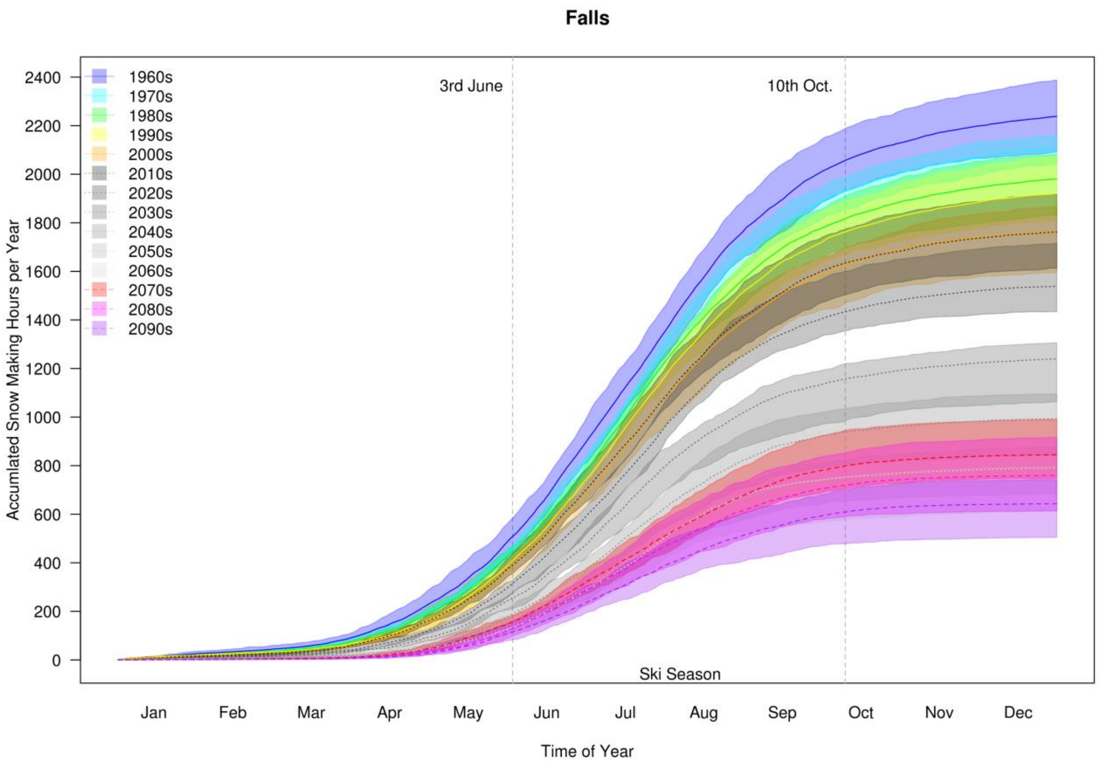
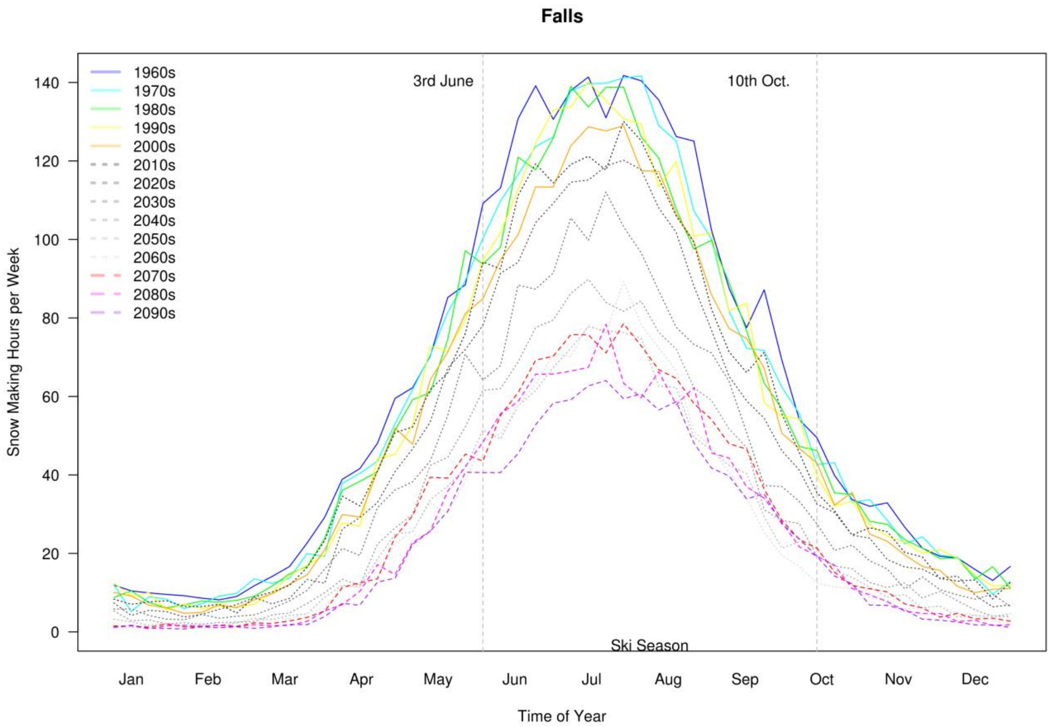


Figure 4.10C: The change in the number of hours suitable for snowmaking between current and future periods based on a threshold of -1°C wet bulb temperature. a) The number of hours per week below the threshold, b) Accumulated snowmaking hours per year

a)



b)

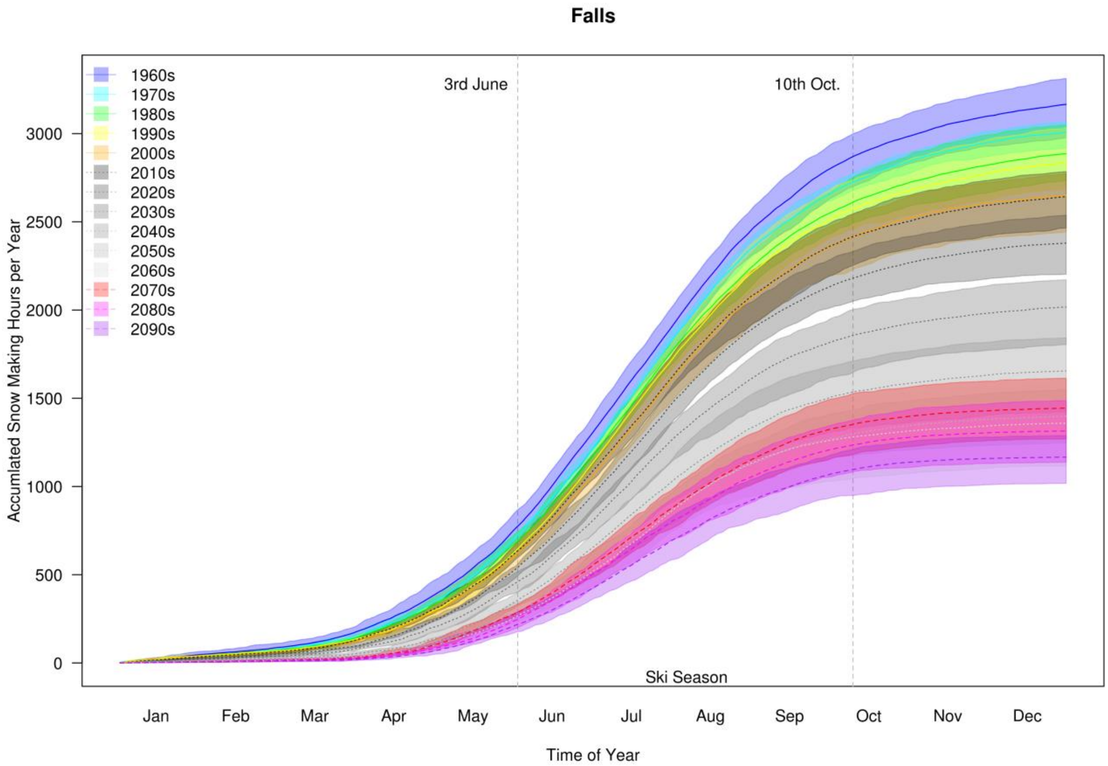


Figure 4.11C: The change in the number of hours suitable for snowmaking between current and future periods based on a threshold of 0.5°C wet bulb temperature. a) The number of hours per week below the threshold, b) Accumulated snowmaking hours per yea

D. MT BAW BAW (elevation 1563m)

This section describes the changes in climate that are projected to occur at the Mt Baw Baw resort. An explanation of the Climate Futures for the Australian Alps projections, the methods used and results from across all of the Victorian Alpine resorts can be found in the main report. The main report also provides important information about the scope of the study and considers the uncertainty associated with projections of future climate.

Relative to recent decades (1961-2010), the projections for Mt Baw Baw by the end of the century, under a high emissions scenario, show:

1. An increase in mean annual temperature of 3-5°C (mean of 4°C);
2. An increase in the number of extreme hot temperatures and a decrease in the number of very cold days;
3. The temperature of the coldest days in winter and the hottest summer days increases by approximately 2.5°C;
4. A mean decrease in annual precipitation of 11%. The range across the six climate models is from a maximum decrease of 20% to a slight decrease of 2%;
5. A decrease in precipitation from July through to October for all climate models;
6. Substantial reductions in snowfall, from 81% to 76% less snowfall than the baseline period (mean reduction of 78%);
7. With warmer temperatures there is a reduction in the proportion of precipitation falling as snow. More snow falling as sleet has implications for the retention of snow;
8. No change in wind speed or wind direction.

D1 Changes between current and future periods

The changes projected to occur at Mt Baw Baw between the current (1961-2010) and future (2070-2099) time periods are shown in Table 4.1D.

Figure 4.1D shows the frequency distribution for key climate variables in the modelled current (1961-2010) and future (2069-2099) time periods. The number of occurrences of a particular value is used to highlight any shifts in the overall distribution, the mean or the variance (spread) of the values for each climate variable. The daily values across all models are shown in Figure 4.2D.

The proportion of precipitation falling as snow in the historical, current and future periods are shown in Figure 4.3D. Fewer snow days in the future means that there will be fewer days when precipitation is 100% snow. There is also a reduction in the proportion of snow, with more snow falling as sleet. This has implications for the retention of natural or artificial snow.

D2 Changes to monthly mean values

A comparison of the multi-model mean monthly values of key climate variables in the current and future time periods is presented in Figure 4.4D. Increases in temperature are evident in every month of the year. In the future, the monthly mean temperature of the winter months, (June, July and August) is projected to be more like that currently experienced in autumn and spring. Temperatures in June, July and August in the future are projected to be similar to those currently experienced in April/May or September. May and September in the future period show temperatures similar to those currently experienced in April or October. This could potentially affect the ability for artificial snow to be laid down in the months leading up to the ski season.

Similarly, mean monthly wet bulb temperatures increase in all months, and show the same shifts in winter towards temperatures currently more typical of autumn and spring. Wet bulb temperature does not increase as much as dry bulb temperature, however, because wet bulb temperature reflects the influence of humidity. Note that this summary of monthly values does not show the very low temperatures because it is based on daily means. More detailed analyses of the number of hours per day suitable for snowmaking at particular threshold temperatures are provided in Section D4.

There are no changes to wind speed or direction in any month of the year. Projections of humidity, however, which showed no change in annual means, is projected to decrease slightly from April to June, with more substantial reductions evident from July to December (Figure 4.4D).

The large range in monthly values for precipitation are due to the range in values across the six climate models (Table 4.1D). However, all models project decreased precipitation to occur during April, and July through to October (Figure 4.5D). In May and June, all models but one show decreased precipitation. In the other months, there is more inconsistency in the direction of change, with some models showing slight increases and others. Substantial reductions in snowfall and snow depth are projected by all climate models in all months (Figure 4.6D, Figure 4.7D). Not only are there fewer days when it snows, but there is reduced snowfall on days when it does snow.

D3 Shifts in the timing and duration of the ski season based on natural snow

The change in the duration and timing of the ski season between current and future periods based on natural snow depth is shown in Figure 4.8D.

All models agrees with observational records that indicate a steady reduction in snow depth over recent decades, from the 1960’s to 2010’s, and the duration of the ski season has contracted, with a later start and earlier finish. Assuming a depth of 30cm is required for skiing, the season length has contracted by 19% relative to the historical period (1960’s) in the model. Relative to the 2000-2010 period, it is projected to contract by 63% by the 2070’s.

D4 Changes to the frequency of suitable snowmaking conditions

The number of hours suitable for snowmaking (below -2°C) before the start of the ski season (June 3rd) at Mt Baw Baw declines from 29 hours in the 1960s to 1 by the end of the century. (Table 4.2D). This represents a drop of approximately 7% per decade, but the decline was as high as 24% in the 1990s. In the 2010's the projections show a slight increase in cold conditions, followed by a further decline of approximately 25% in the next decade (2020). Opportunities for snowmaking relative to the 2010's are halved by 2030-2040.

If snow is made at warmer temperatures, more hours are available for snowmaking for longer into the future, but still decline to 3 hours below -1°C and 18 hours below 0.5°C by the final decade of the century.

The drop in conditions suitable for snowmaking throughout the year is presented graphically for the three wet bulb temperature thresholds (-2°C, -1°C, 0.5°C) in Figures 4.9D to 4.11D. Values for the decades 1960-2010 and 2070-2090 are based on the multi-model mean of 3 hourly data from the dynamically downscaled model runs, while the decades 2020-2060 are the multi-model mean of 3 hourly data from the statistically derived values (see Box 2 in the main report). The results show a gradual decline from 1960 to 2000, followed by a marked drop in available hours for snowmaking between the 2020's and 2030's. If warmer thresholds are accepted, with the associated trade-offs in cost and quality of snow, the number of hours suitable for making snow is higher than at colder temperatures.

The accumulation of hours below different threshold temperatures can be used to indicate the start of the ski season, and the quality of snow that may be made (Figures 4.9D to 4.11D). In the 1960's, approximately 30 hours below -2°C wet bulb temperature had accumulated, on average, before the ski season start date (3rd June). By 2020 this is projected to decline to 100 hours available for making snow. By 2070, the number of hours below -2°C accumulated before 3rd June is close to zero. We use the 1960s value (350 hours below -2°C) to indicate the climatic beginning of the ski season (rather than the calendar date). In these terms, the changes equate to a relative shift in the start of the ski season from the 3rd June (1960's) to the 24th June in the 2020's, the 14th July in the 2030's and 21st August by the 2040's. By the 2050's, the season start date based on accumulated snowmaking hours shifts to after the end of the current season (10th October).

As natural snow declines, more snow will need to be made, under warmer conditions, to achieve the target snow depth profile throughout the season (see Table 2 in the main report). At Mt Baw Baw, by 2070, almost all snow will need to be artificially produced, in approximately 70% fewer snowmaking hours (relative to 2010). However, if snow is made at warmer temperatures, snowmaking hours can be maintained at current (2010) levels until the 2030's (-1°C wet bulb temperature) or the 2090's (-0.5°C). For example, by the start of the season, at present (2010) there are about 20 snowmaking hours below -2°C per week. By 2070 this drops to 6 hours, but if the warmer threshold of 0.5°C is used, 25 hours remain.

Table 4.1D: Projected change in key climate variables at Mt Baw Baw between the current (1961-2010) and future (2070-2099) time periods. The multi-model mean is shown for each 30 year period, with the range of change between climate models shown in brackets.

	Temperature (°C)			Wet bulb temperature (°C)			Precipitation (mm)		Snowfall (mm)		Wind speed (m/s)	Wind direction (m/s)
	Minimum Winter	Maximum Summer	Mean annual	Minimum Winter	Maximum Summer	Mean annual	Mean Daily	Mean Annual	Maximum weekly	Mean Annual Maximum	Mean annual	
Current	-1.47 (-1.73, -1.34)	-2.88 (-3.06, -2.79)	9.23 (9.08, 9.42)	-9.60 (-12.18, -7.03)	21.49 (20.58, 22.26)	6.34 (6.25, 6.49)	5.00 (4.89, 5.09)	1825	6.08 (5.57, 7.10)	316.16	3.23 (3.21, 3.27)	173.87 (172.38, 176.37)
Future	1.10 (0.64 , 1.71)	-0.52 (-0.88, 0.00)	13.12 (12.21, 13.97)	-5.45 (-6.33, -4.31)	29.00 (24.03, 30)	9.61 (9.15, 10.05)	4.45 (3.95, 5.00)	1624.25	1.37 (1.05, 1.67)	71.24	3.25 (3.22, 3.29)	173.32 (169.81, 177.46)
Change	2.57 (2.09, 3.43)	2.36 (1.98, 3.06)	3.89 (2.99, 4.89)	4.14 (2.02, 6.58)	7.51 (2.64, 9.42)	3.27 (2.81, 3.77)	-0.54 (-1.14, -0.01)	-11% (-19%, -2%)	-4.71 (-5.99, -4.21)	-78% (-81%,-76%)	0.02 (-0.03, 0.07)	-0.55 (-4.63, 3.97)

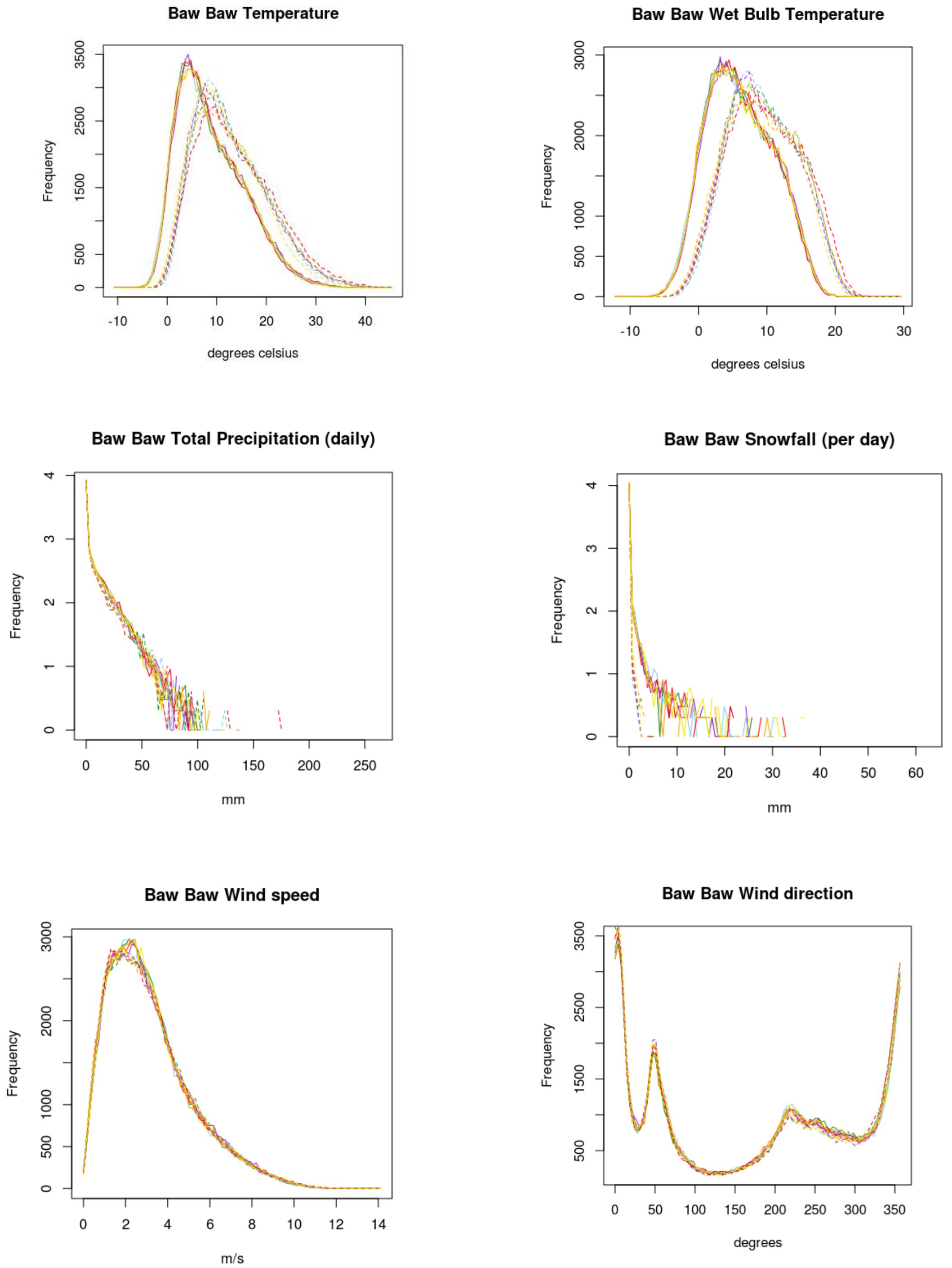


Figure 4.1D: Frequency distribution of key climate variables in the modelled current (full lines) and future (dashed lines) time periods. The six climate models are shown in different colours. log values for daily precipitation and snowfall are shown.

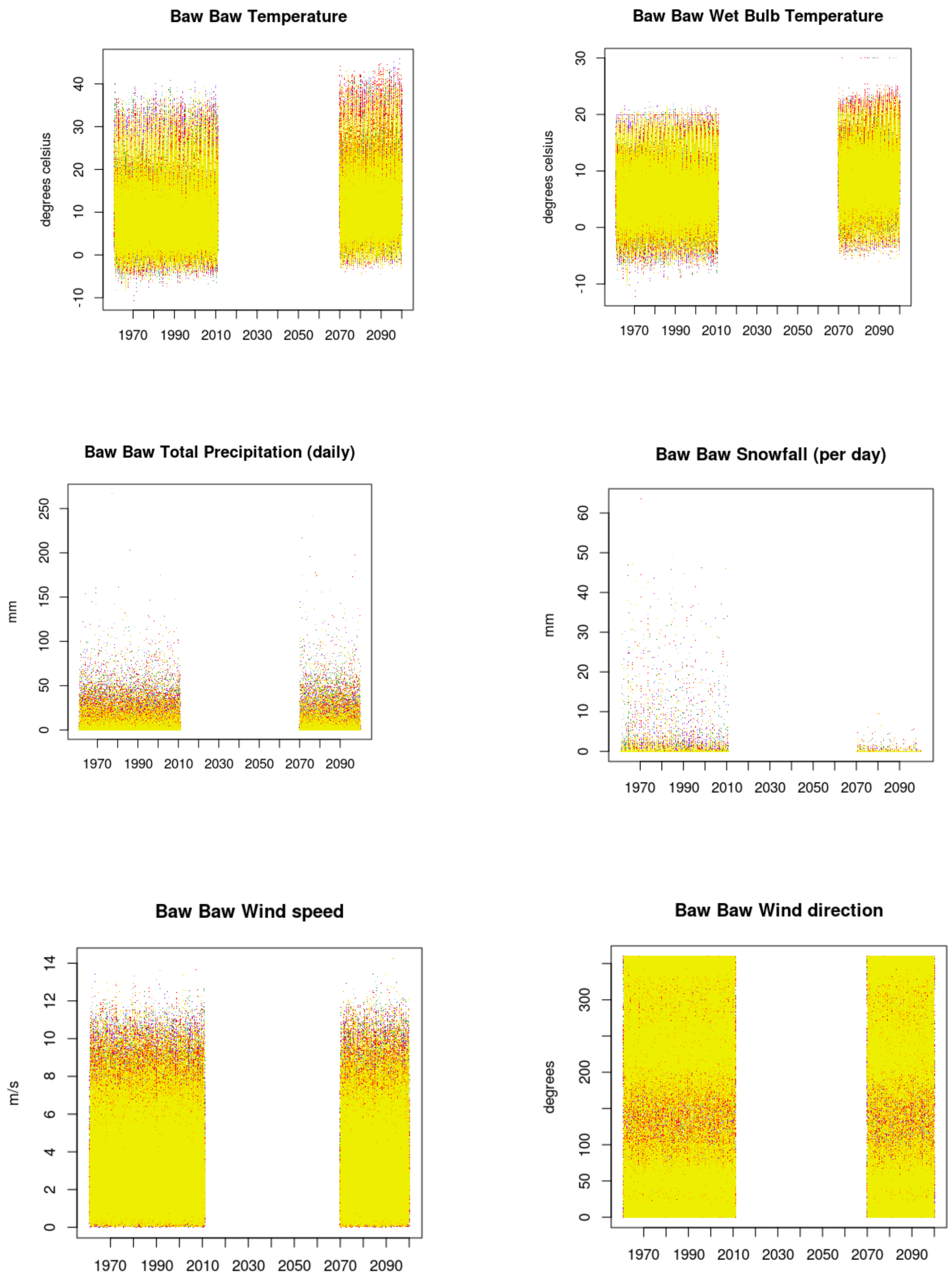


Figure 4.2D: Daily values of key climate variables from the six climate models showing the modelled periods, 1961-2010 and 2070-2099.

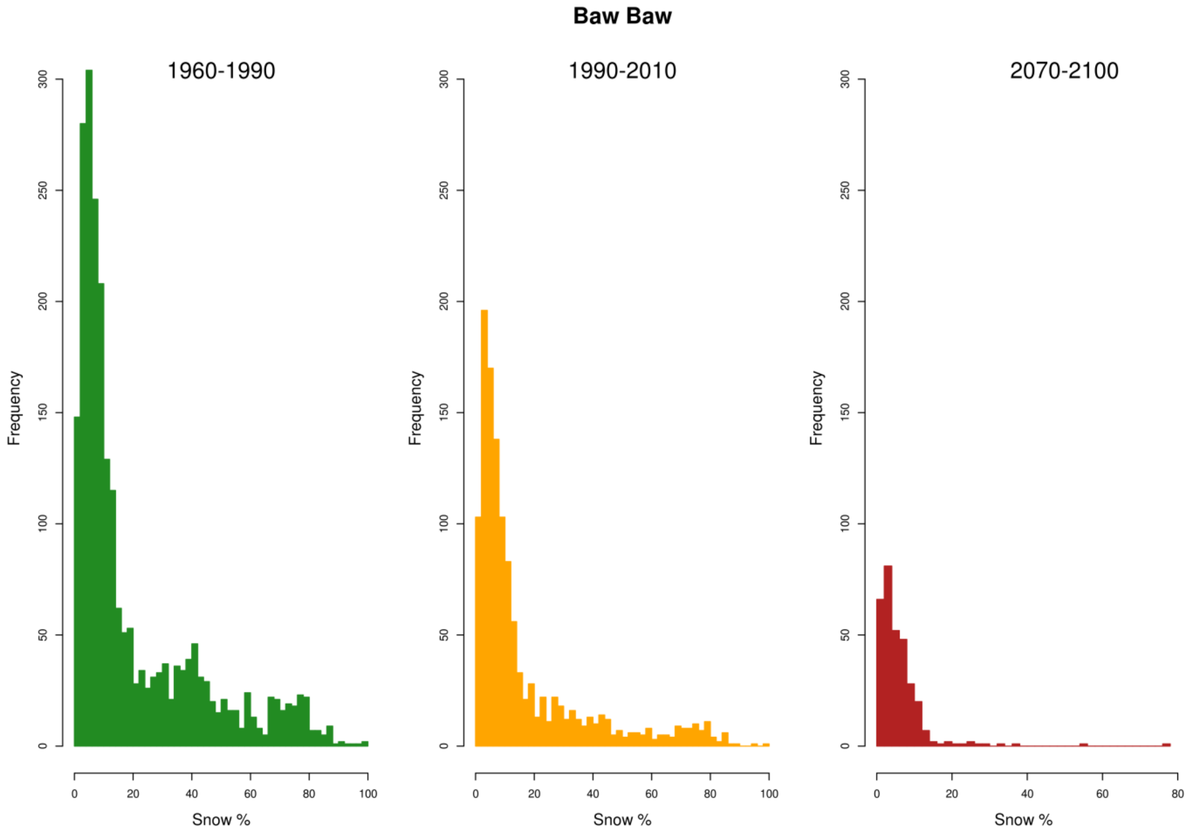
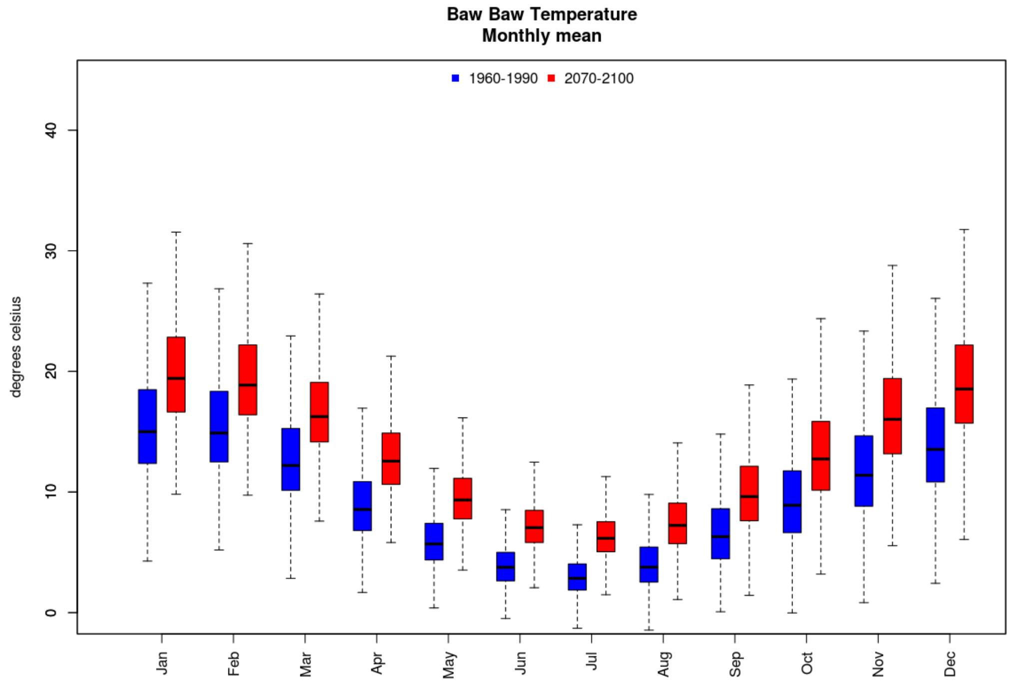
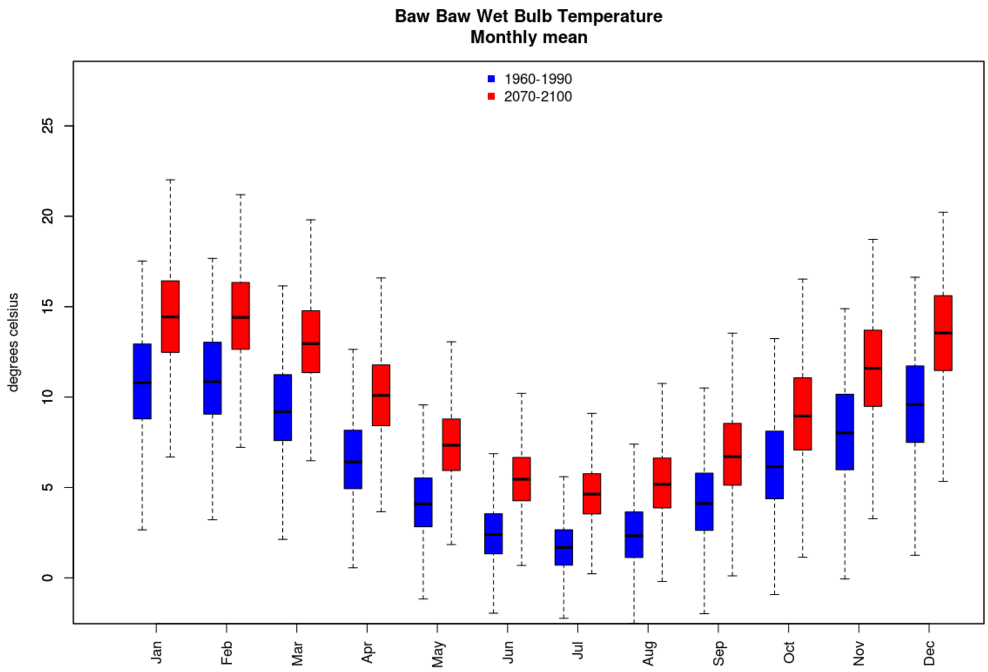
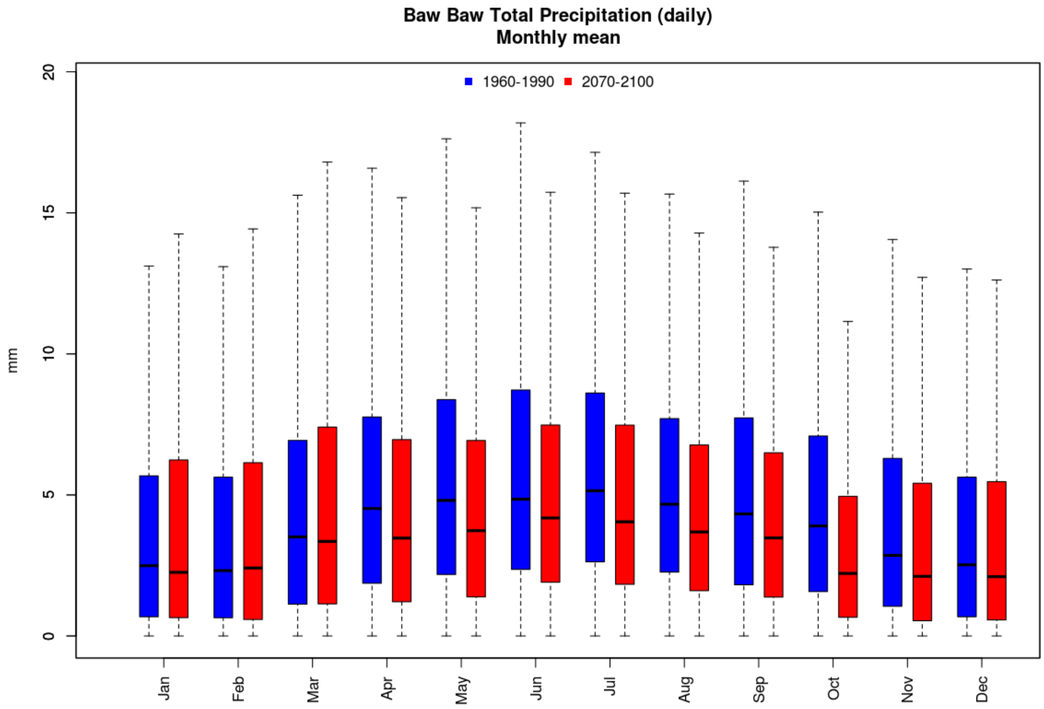
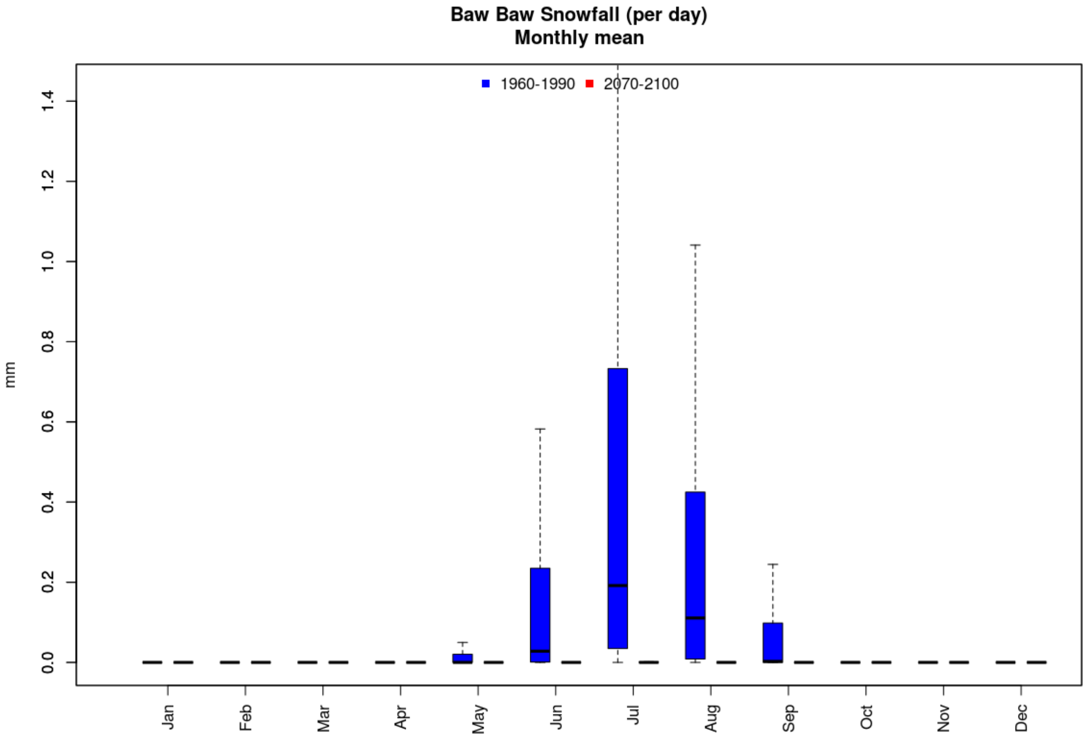


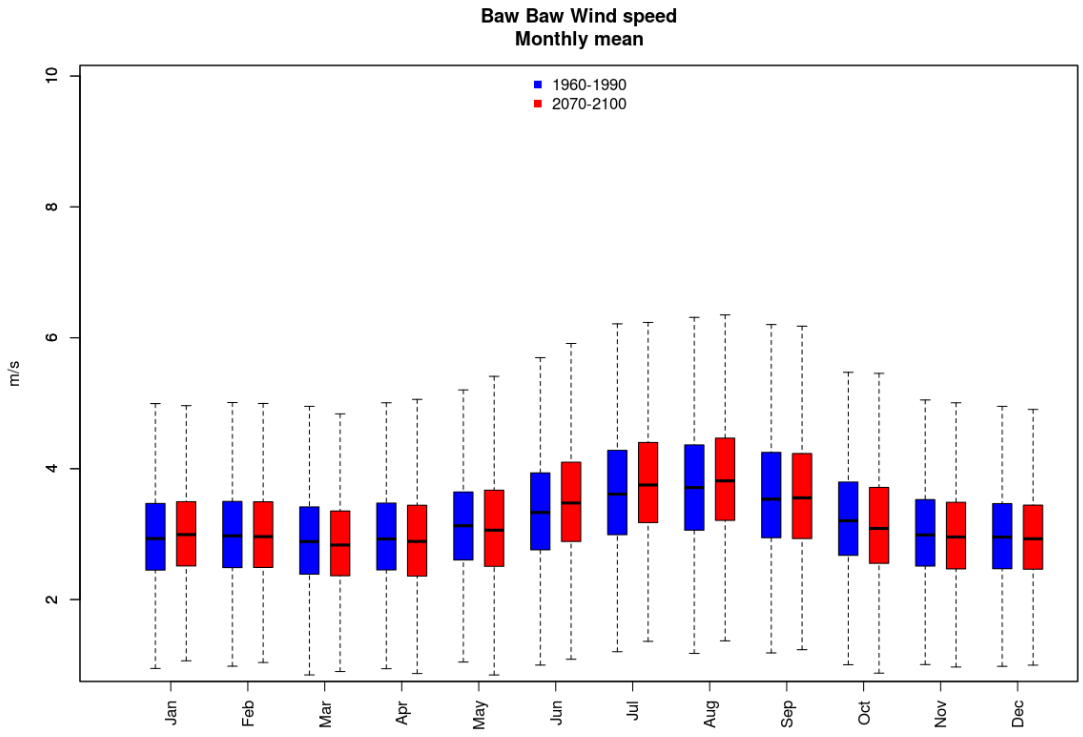
Figure 4.3D: The proportion of precipitation falling as snow in the historical (1960-1990), current (1990-2010) and future (2070-2100) periods.

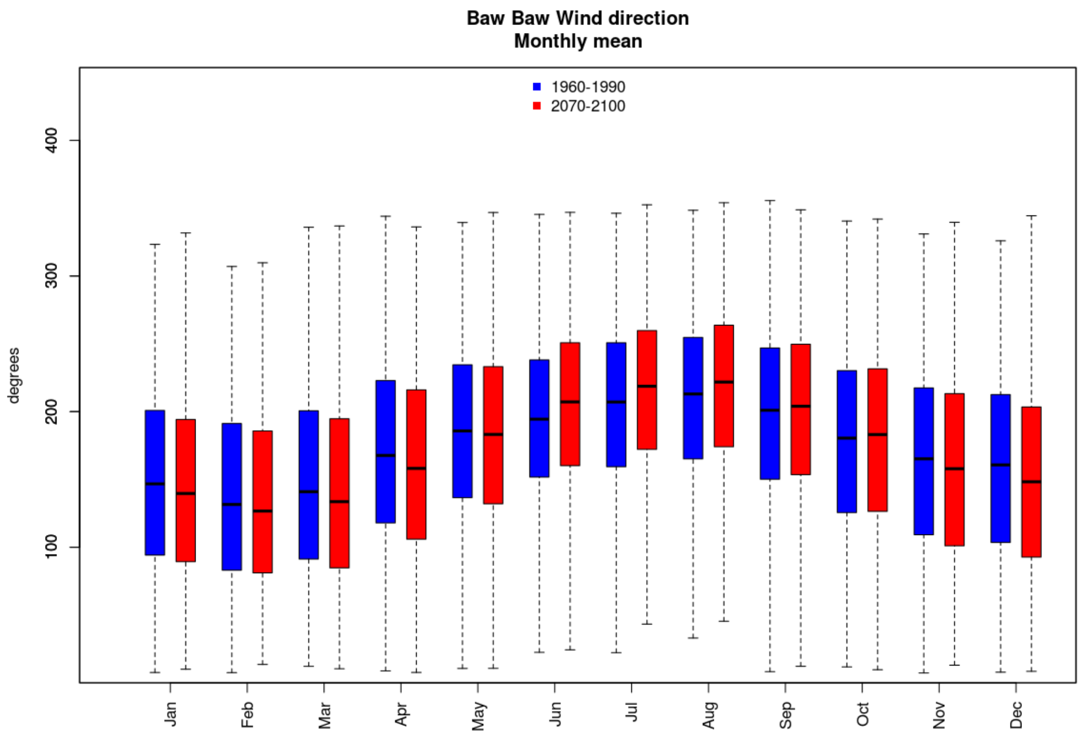

Baw Baw Temperature
Monthly mean
1960-1990
2070-2100
degrees celsius
0
10
20
30
40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Baw Baw Wet Bulb Temperature
Monthly mean
1960-1990
2070-2100
degrees celsius
0
5
10
15
20
25
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Baw Baw Total Precipitation (daily)
Monthly mean
1960-1990
2070-2100
mm
0
5
10
15
20
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Baw Baw Snowfall (per day)
Monthly mean
1960-1990
2070-2100
mm
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Baw Baw Wind speed
Monthly mean
1960-1990
2070-2100
m/s
2
4
6
8
10
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Baw Baw Wind direction
Monthly mean
1960-1990
2070-2100
degrees
100
200
300
400
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

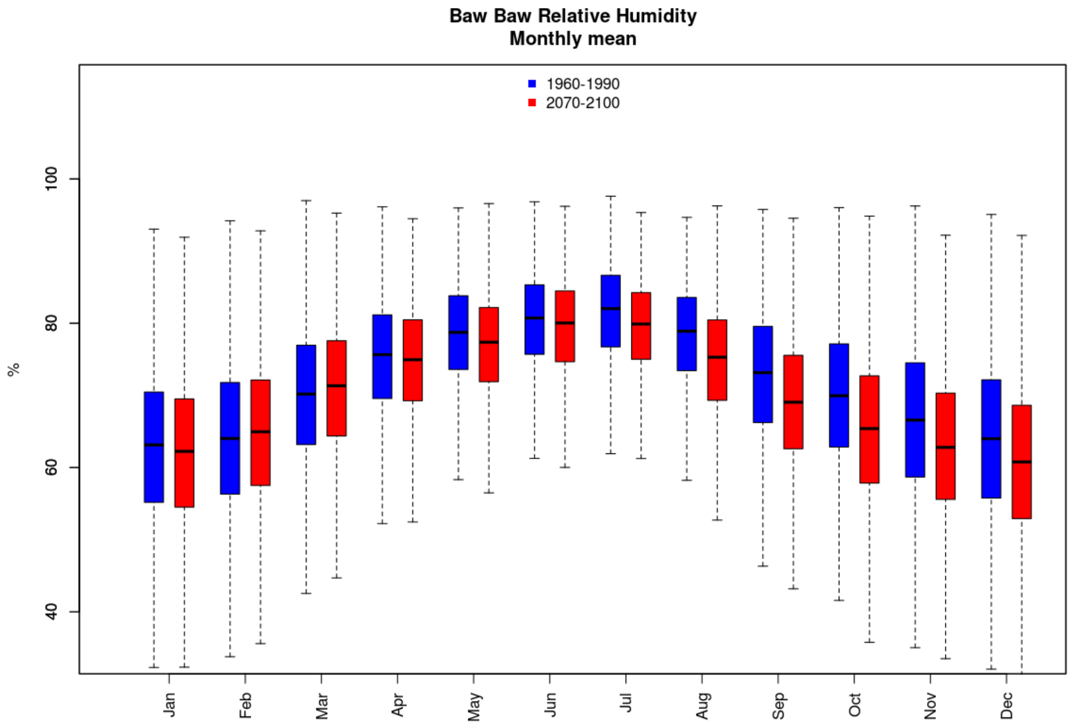


Figure 4.4D: The multi-model monthly mean values of key climate variables in the current (blue) and future (red) time periods. The bottom and top of the box are the 25th and 75th percentiles, the bar is the median, and the whiskers go to the most extreme data point which is no more than +/- 1.5 times the interquartile range from the box. Note that snowfall is the amount of snowfall on days when it snows.

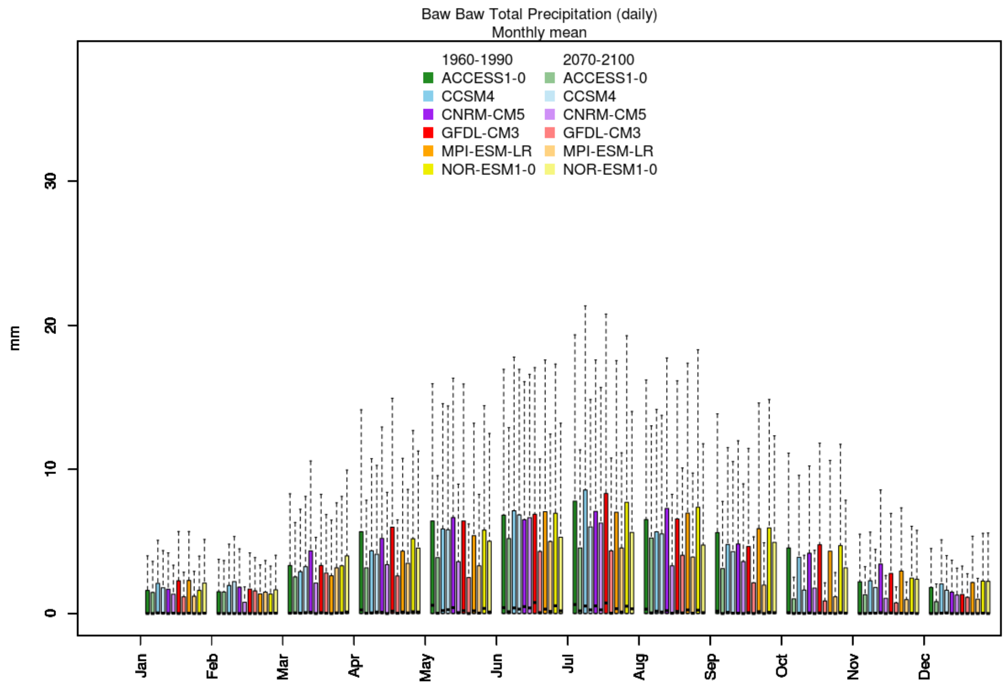


Figure 4.5D: The range in monthly mean precipitation projected by the six climate models in the current and future time periods.

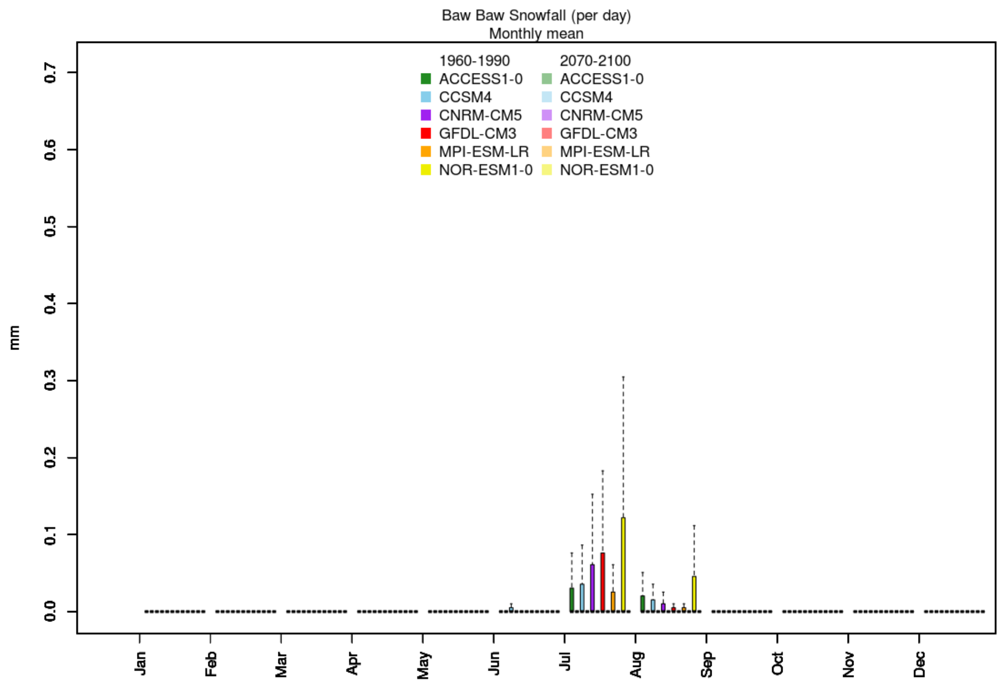


Figure 4.6D: The range in monthly mean snowfall projected by the six climate models in the current and future time periods.

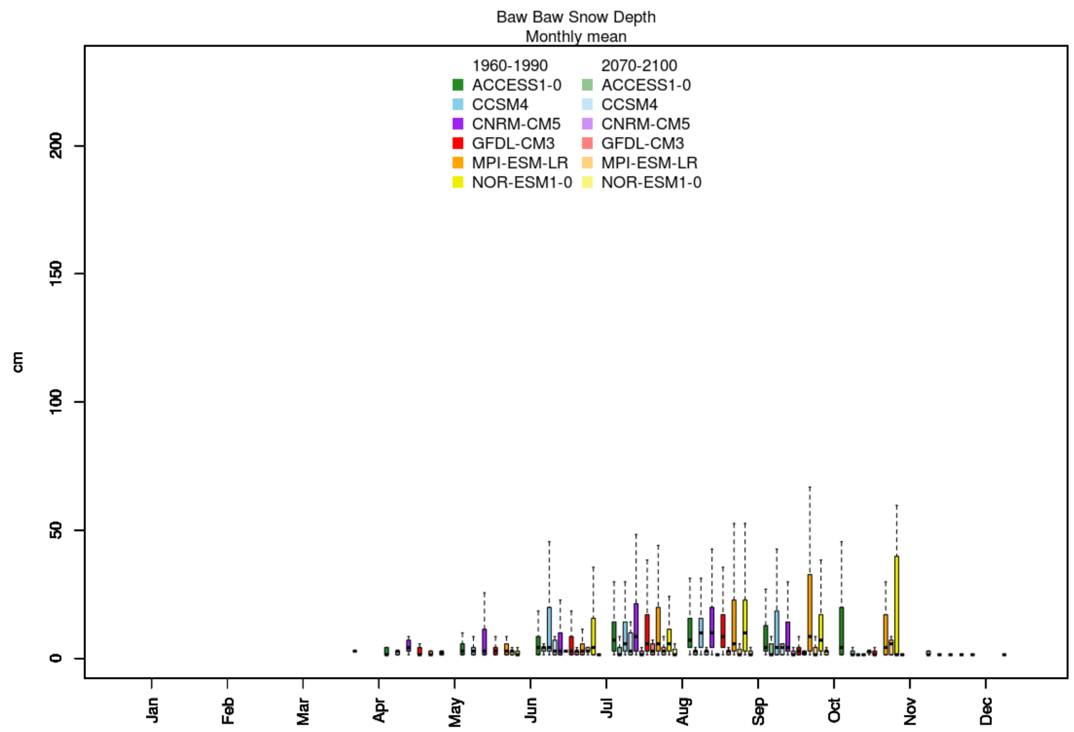


Figure 4.7D: The range in monthly mean snow depth projected by the six climate models in the current and future time periods.

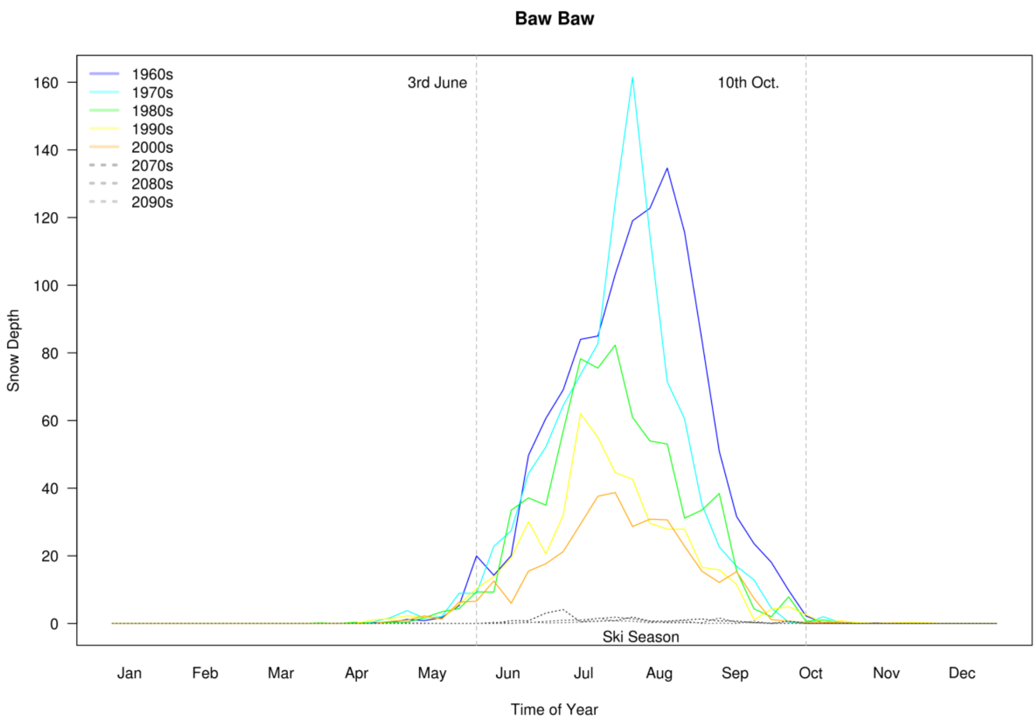


Figure 4.8D: The change in the ski season between current and future periods based on natural snow depth.

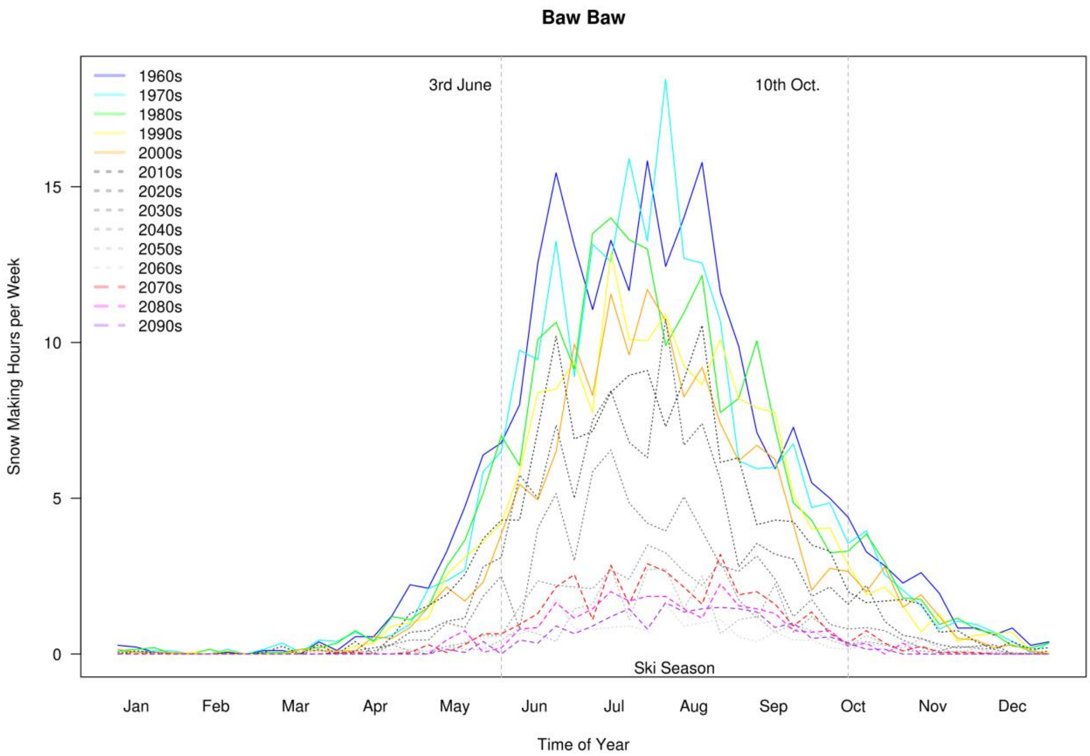
Table 4.2D: The number of snowmaking hours that accumulate at Mt Baw Baw by June 3rd based on three different thresholds for wet bulb temperatures (-2°C, -1°C, 0.5°C). Numbers in brackets show the range across the climate models. Values for the decades 1960-2010 and 2070-2090 are based on 3 hourly model output while the decades 2020-2060 are statistically derived.

Decade	**Number of hours above Wet Bulb temperature threshold**		
	-2°C	**-1°C**	**0.5°C**
1960s	29 (16 to 46)	66 (51 to 90)	179 (147 to 227)
1970s	24 (16 to 33)	55 (48 to 70)	161 (148 to 178)
1980s	25 (19 to 34)	57 (45 to 65)	156 (142 to 165)
1990s	18 (9 to 29)	45 (28 to 65)	137 (109 to 164)
2000s	14 (11 to 20)	38 (30 to 46)	116 (101 to 139)
2010s	17 (12 to 22)	41 (28 to 53)	126 (95 to 141)
2020s	10 (7 to 16)	28 (22 to 38)	93 (83 to 111)
2030s	8 (4 to 11)	21 (14 to 29)	68 (47 to 86)
2040s	2 (0 to 4)	8 (4 to 13)	37 (19 to 53)
2050s	1 (0 to 2)	6 (3 to 10)	27 (18 to 38)
2060s	2 (2 to 3)	6 (4 to 9)	27 (18 to 31)
2070s	2 (1 to 4)	8 (4 to 11)	32 (23 to 41)
2080s	1 (0 to 4)	5 (2 to 11)	25 (13 to 46)
2090s	1 (0 to 2)	3 (0 to 5)	18 (8 to 26)

Table 4.3D: Shift in ski season start date at Mt Baw Baw for three different thresholds for wet bulb temperatures (-2°C, -1°C, 0.5°C). Numbers in brackets show the range across the climate models. Values for the decades 1960-2010 and 2070-2090 are based on 3 hourly model output while the decades 2020-2060 are statistically derived. NA indicates that the season start date shifts to after the end of the current season (10th October).

Decade	**Shift in season start date relative to the 1960's (Days)**		
	-2°C	**-1°C**	**0.5°C**
1970s	0 (0 to 0)	0 (0 to 0)	0 (0 to 0)
1980s	3 (-1 to 9)	3 (1 to 10)	2 (-1 to 10)
1990s	4 (-4 to 9)	5 (1 to 10)	5 (1 to 11)
2000s	11 (7 to 22)	10 (10 to 13)	9 (8 to 12)
2010s	18 (9 to 25)	17 (13 to 22)	15 (13 to 20)
2020s	14 (6 to 20)	14 (11 to 18)	12 (11 to 18)
2030s	21 (14 to 28)	21 (26 to 26)	21 (20 to 27)
2040s	37 (29 to 48)	37 (44 to 39)	34 (38 to 35)
2050s	76 (55 to 94)	70 (74 to 68)	60 (65 to 61)
2060s	NA (74 to NA)	120 (91 to NA)	85 (72 to 103)
2070s	NA (NA to NA)	NA (NA to NA)	114 (NA to 105)
2080s	91 (89 to 97)	82 (92 to 81)	67 (71 to 68)
2090s	NA (NA to 136)	103 (NA to 95)	81 (NA to 75)

a)



b)

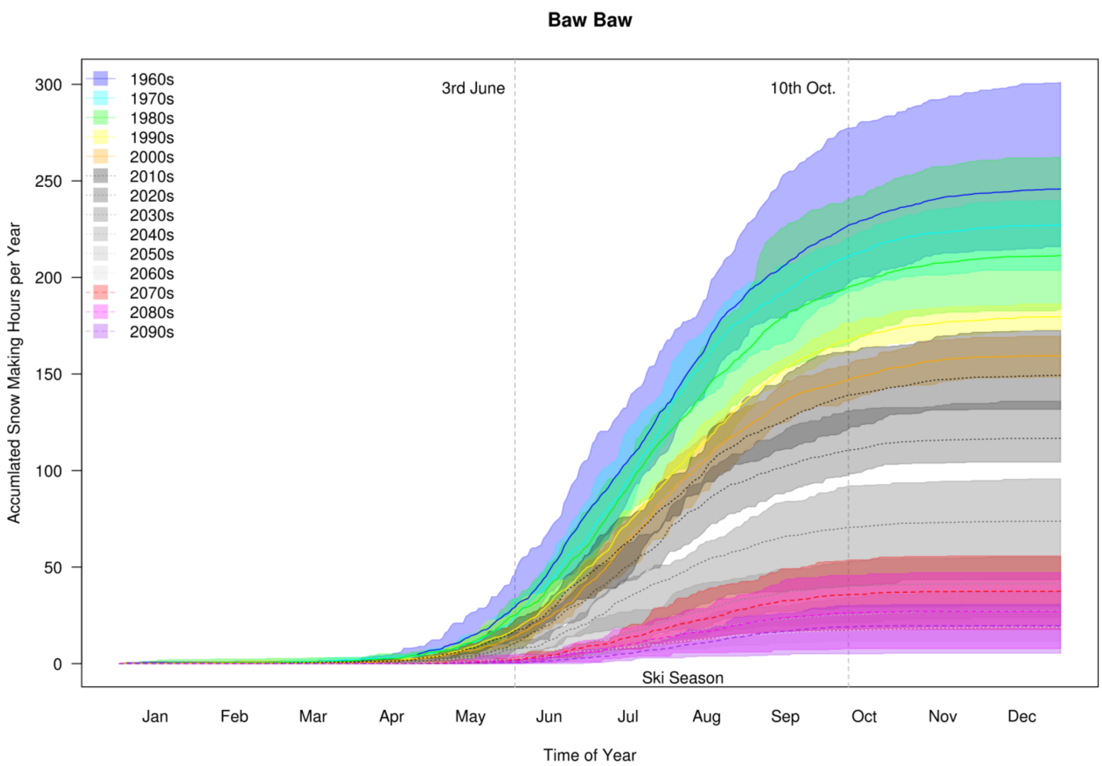
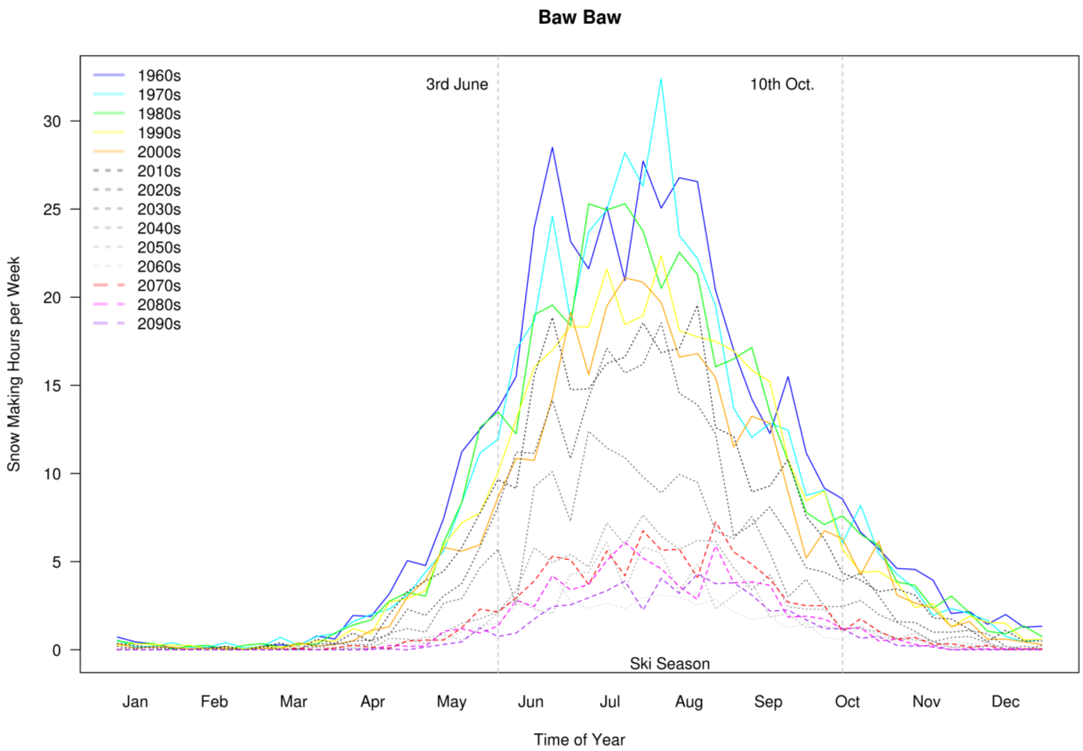


Figure 4.9D: The change in the number of hours suitable for snowmaking between current and future periods based on a threshold of -2°C wet bulb temperature. a) The number of hours per week below the threshold, b) Accumulated snowmaking hours per year

a)



b)

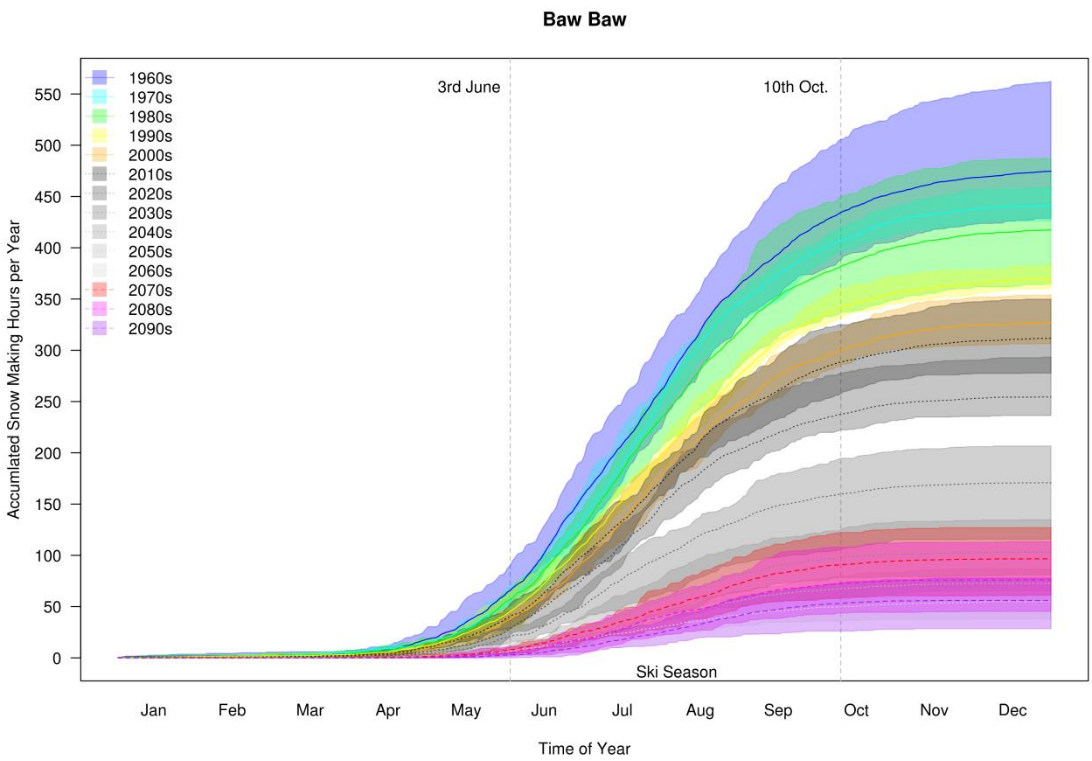
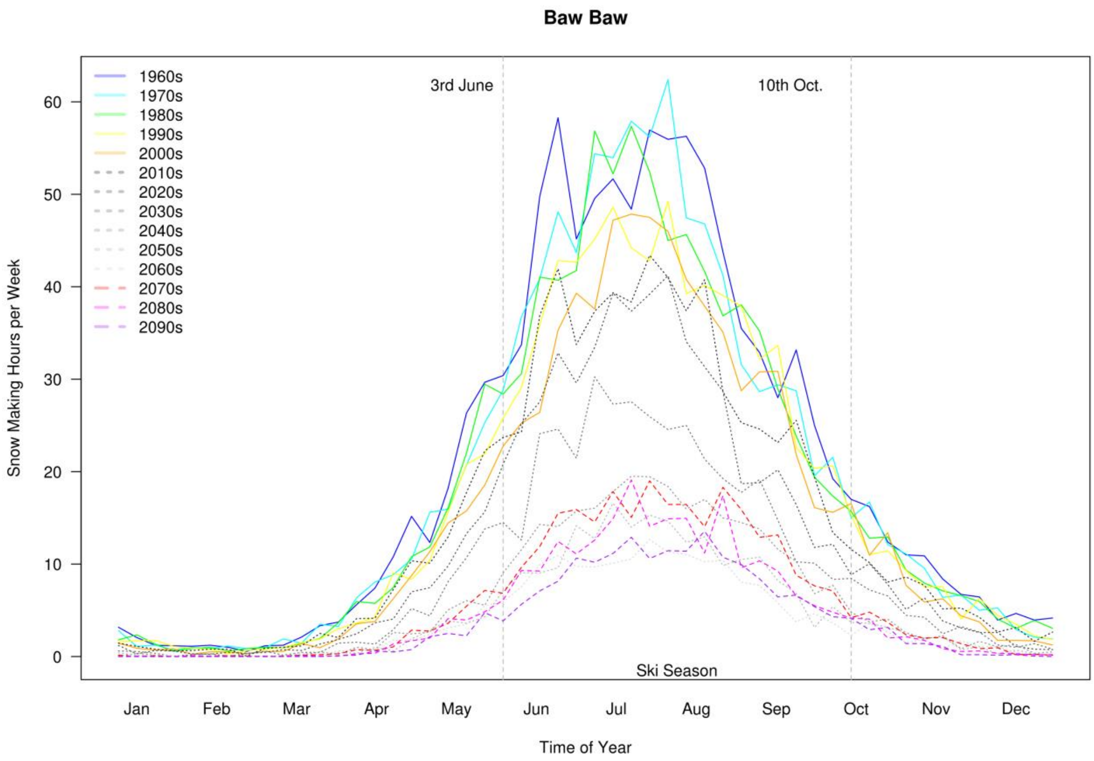


Figure 4.10D: The change in the number of hours suitable for snowmaking between current and future periods based on a threshold of -1°C wet bulb temperature. a) The number of hours per week below the threshold, b) Accumulated snowmaking hours per year

a)



b)

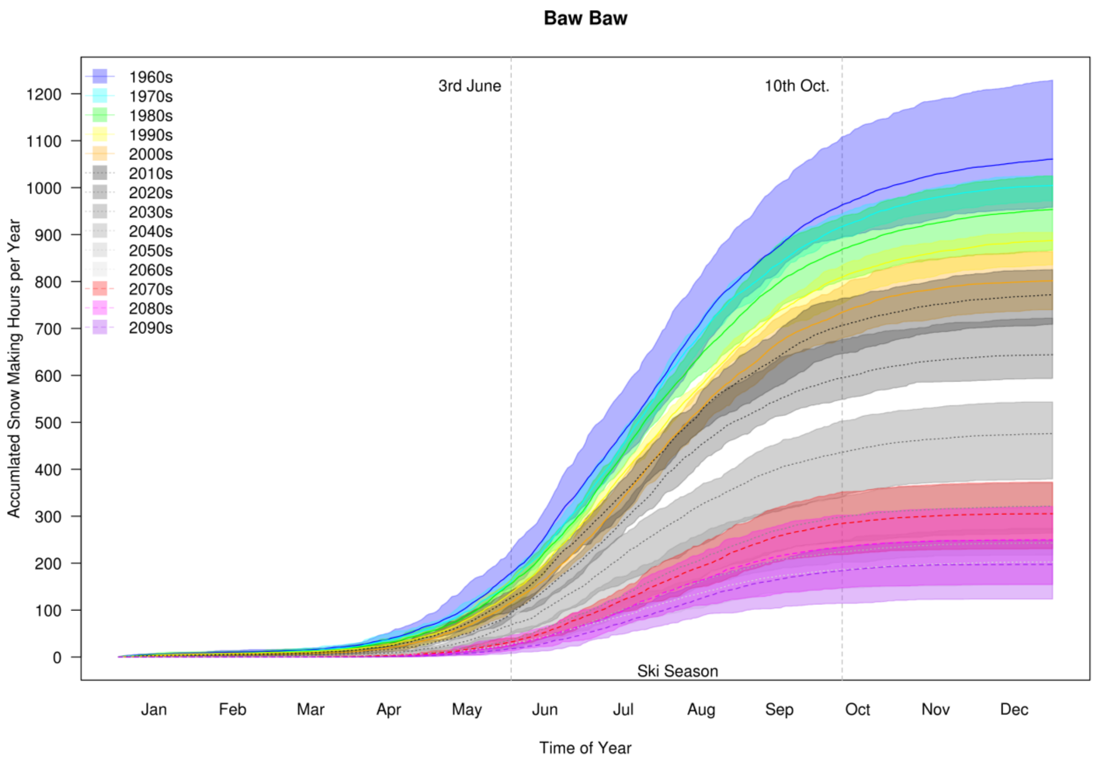


Figure 4.11D: The change in the number of hours suitable for snowmaking between current and future periods based on a threshold of 0.5°C wet bulb temperature. a) The number of hours per week below the threshold, b) Accumulated snowmaking hours per year

E. LAKE MOUNTAIN (elevation 1463m)

This section describes the changes in climate that are projected to occur at the Lake Mountain resort. An explanation of the Climate Futures for the Australian Alps projections, the methods used and results from across all of the Victorian Alpine resorts can be found in the main report. The main report also provides important information about the scope of the study and considers the uncertainty associated with projections of future climate.

Relative to recent decades (1961-2010), the projections for Lake Mountain by the end of the century, under a high emissions scenario, show:

1. An increase in mean annual temperature of 3-5°C (mean of 4°C);
2. An increase in the number of extreme hot temperatures and a decrease in the number of very cold days;
3. The temperature of the coldest days in winter increases by approximately 2.5°C, while the temperature of the hottest summer days increase by approximately 5°C;
4. A mean decrease in annual precipitation of 13%. However, a maximum decrease of 20% to a slight increase of +3% is shown across the six climate models;
5. A decrease in precipitation from April through to October for all climate models;
6. Substantial reductions in snowfall, from 69% to 35% less snowfall than the baseline period (mean reduction of 60%);
7. With warmer temperatures there is a reduction in the proportion of precipitation falling as snow. More snow falling as sleet has implications for the retention of snow;
8. No change in wind speed or wind direction.

E1 Changes between current and future periods

The changes projected to occur at Lake Mountain between the current (1961-2010) and future (2070-2099) time periods are shown in Table 4.1E.

Figure 4.1E shows the frequency distribution for key climate variables in the modelled current (1961-2010) and future (2069-2099) time periods. The number of occurrences of a particular value is used to highlight any shifts in the overall distribution, the mean or the variance (spread) of the values for each climate variable. The shape of the distribution of temperatures (wet and dry bulb) does not change, but there is a shift towards higher temperatures across the distribution. There is an increase in the number of extreme hot temperatures and a decrease in the number of very cold days.

The daily values across all models are shown in Figure 4.2E.

The proportion of precipitation falling as snow in the historical, current and future periods are shown in Figure 4.3E. Fewer snow days in the future means that there will be fewer days when precipitation is 100% snow. There is also a reduction in the proportion of snow, with more snow falling as sleet. This has implications for the retention of natural or artificial snow.

E2 Changes to monthly mean values

A comparison of the multi-model mean monthly values of key climate variables in the current and future time periods is presented in Figure 4.4E. Increases in temperature are evident in every month of the year. In the future, the monthly mean temperature of the winter months, (June, July and August) is projected to be more like that currently experienced in autumn and spring. Temperatures in June, July and August in the future are projected to be similar to those currently experienced in May or September. May and September in the future period show temperatures similar to those currently experienced in April or October. This could potentially affect the ability for artificial snow to be laid down in the months leading up to the ski season.

Similarly, mean monthly wet bulb temperatures increase in all months, and show the same shifts in winter towards temperatures currently more typical of autumn and spring. Wet bulb temperature does not increase as much as dry bulb temperature, however, because wet bulb temperature reflects the influence of humidity. Note that this summary of monthly values does not show the very low temperatures because it is based on daily means. More detailed analyses of the number of hours per day suitable for snowmaking at particular threshold temperatures are provided in Section E4.

There are no changes to wind speed or direction in any month of the year. Projections of humidity, however, which showed no change in annual means, is projected to decrease slightly from April through to August, with more substantial reductions evident in September, October, November and December (Figure 4.4E).

The large range in monthly values for precipitation are due to the range in values across the six climate models (Table 4.1E). However, all models project decreased precipitation to occur during the months April through to October (Figure 4.5E). In the other months, there is more inconsistency in the direction of change, with some models showing slight increases and others decreases. Substantial reductions in snowfall and snow depth are projected by all climate models in all months (Figure 4.6E, Figure 4.7E). Not only are there fewer days when it snows, but there is reduced snowfall on days when it does snow.

E3 Shifts in the timing and duration of the ski season based on natural snow

The change in the duration and timing of the ski season between current and future periods based on natural snow depth is shown in Figure 4.8E.

All models agrees with observational records that indicate a steady reduction in snow depth over recent decades, from the 1960's to 2010's, and the duration of the ski season has contracted, with a later start and earlier finish. Assuming a depth of 30cm is required for skiing, the season length has contracted by 27% relative to the historical period (1960's) in the model. Relative to the 2000-2010 period, it is projected to contract by 74% by the 2070's.

E4 Changes to the frequency of suitable snowmaking conditions

The number of hours suitable for snowmaking (below -2°C) before the start of the ski season (June 3rd) at Lake Mountain declines from 61 hours in the 1960s to 4 by the end of the century resulting in less than 7% of the historical snowmaking opportunities remaining by the end of the century (Table 4.2E). This represents a drop of approximately 7% per decade, but the decline is as high as 18% in the 2020s, followed by further declines of 10% in the 2030's and 16% in the 2040's. Opportunities for snowmaking relative to the 2010's are halved by 2030-2040.

If snow is made at warmer temperatures, more hours are available for snowmaking for longer into the future, but still decline to 10hours below -1°C and 34 hours below 0.5°C by the final decade of the century.

The drop in conditions suitable for snowmaking throughout the year is presented graphically for the three wet bulb temperature thresholds (-2°C, -1°C, 0.5°C) in Figures 4.9E to 4.11E. Values for the decades 1960-2010 and 2070-2090 are based on the multi-model mean of 3 hourly data from the dynamically downscaled model runs, while the decades 2020-2060 are the multi-model mean of 3 hourly data from the statistically derived values (see Box 2 in the main report). The results show a gradual decline from 1960 to 2000, followed by a marked drop in available hours for snowmaking between the 2020's and 2030's. If warmer thresholds are accepted, with the associated trade-offs in cost and quality of snow, the number of hours suitable for making snow is higher than at colder temperatures.

The accumulation of hours below different threshold temperatures can be used to indicate the start of the ski season, and the quality of snow that may be made (Figures 4.9E to 4.11E). In the 1960's, approximately 50 hours below -2°C wet bulb temperature had accumulated, on average, before the ski season start date (3rd June). By 2020 this is projected to decline to 25 hours available for making snow. By 2070, almost no hours below -2°C accumulate before 3rd June. We use the 1960s value (350 hours below -2°C) to indicate the climatic beginning of the ski season (rather than the calendar date). In these terms, the changes equate to a relative shift in the start of the ski season from the 3rd June (1960's) to the 26th June in the 2020's, the 14th July in the 2030's and the 17th August in the 2040's. By the end of the century, the same number of accumulated snowmaking hours is not reached at any time of the year.

As natural snow declines, more snow will need to be made, under warmer conditions, to achieve the target snow depth profile throughout the season (see Table 2 in the main report). At Lake Mountain, by 2070, almost all snow will need to be artificially produced, in approximately 80% fewer snowmaking hours (relative to 2010). However, if snow is made at warmer temperatures, snowmaking hours can be maintained at current (2010) levels until the 2030's (-1°C wet bulb temperature) or the 2090's (-0.5°C). For example, by the start of the season, at present (2010) there are about 10 snowmaking hours below -2°C per week. By 2070 this drops to 2 hours, but if the warmer threshold of 0.5°C is used, 10 hours remain.

Table 4.1E: Projected change in key climate variables at Lake Mountain between the current (1961-2010) and future (2070-2099) time periods. The multi-model mean is shown for each 30 year period, with the range of change between climate models shown in brackets.

	Temperature (°C)			Wet bulb temperature (°C)			Precipitation (mm)		Snowfall (mm)		Wind speed (m/s)	Wind direction (m/s)
	Minimum Winter	Maximum Summer	Mean annual	Minimum Winter	Maximum Summer	Mean annual	Mean Daily	Mean Annual	Maximum weekly	Mean Annual Maximum	Mean annual	
Current	-2.88 (-3.14, -2.76)	26.38 (25.87, 27.02)	8.35 (8.20, 8.52)	-12.56 (-14.90, -11.42)	21.46 (21.05, 22.23)	5.76 (5.68, 5.90)	4.03 (3.93, 4.15)	1470.95	13.45 (10.97, 15.28)	699.4	3.37 (3.34, 3.39)	248.75 (247.67, 249.55)
Future	-0.17 (-0.61, 0.36)	31.58 (29.55, 33.41)	12.39 (11.40, 13.34)	-7.90 (-8.71, -7.38)	30 (30, 30)	9.14 (8.68, 9.63)	3.52 (3.13, 4.02)	1284.8	5.45 (3.35, 9.91)	283.4	3.36 (3.28, 3.44)	250.01 (248.07, 252.21)
Change	2.72 (2.26, 3.51)	5.20 (3.20, 7.41)	4.04 (3.06, 5.14)	4.65 (3.41, 6.19)	8.54 (7.77, 8.95)	3.38 (2.93, 3.93)	-0.51 (-1.01, 0.04)	-13% (-20%, -3%)	-8.00 (-10.26, -5.38)	-59% (-69%,-35%)	-0.01 (-0.08, 0.05)	1.26 (-1.41, 3.82)

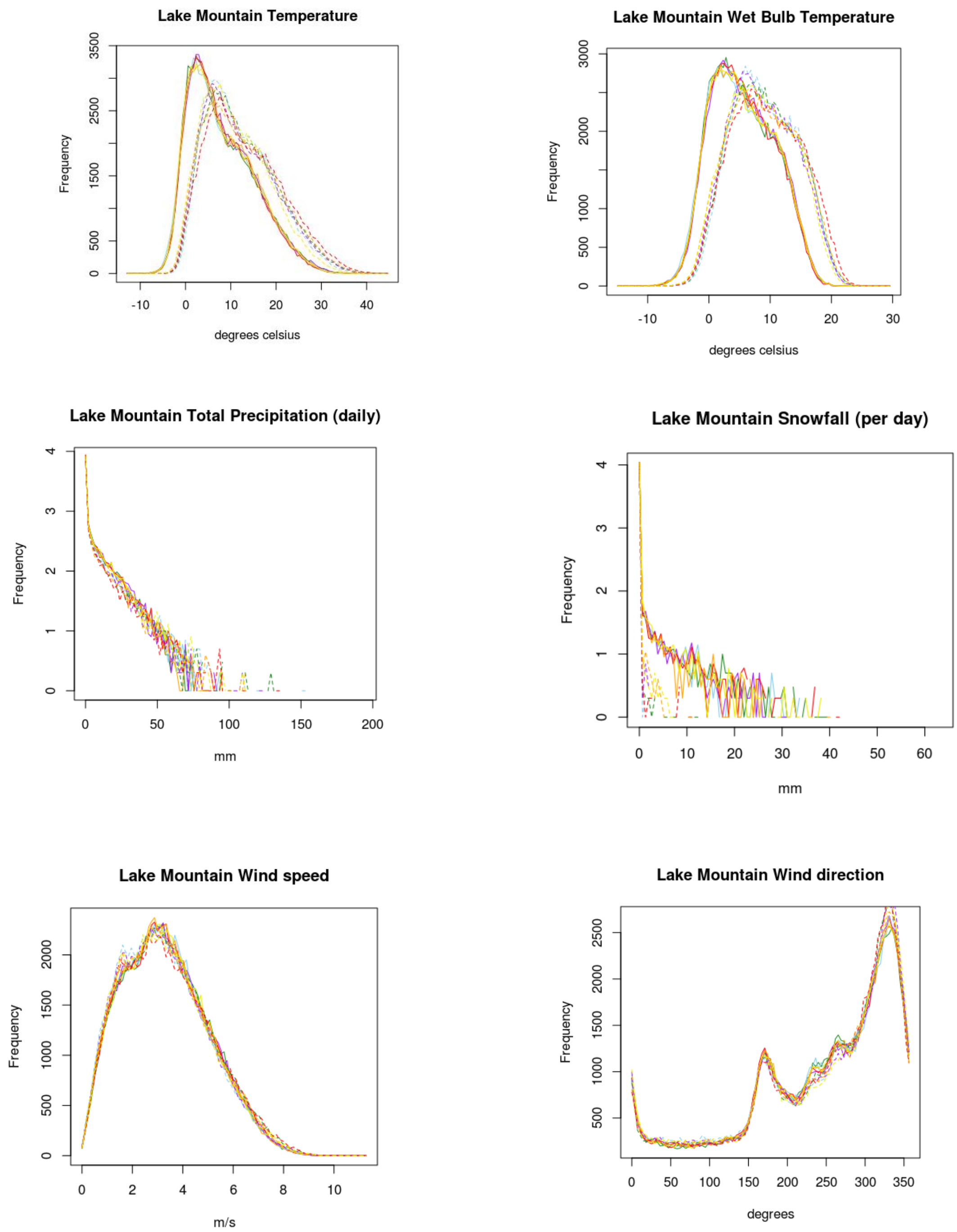


Figure 4.1E: Frequency distribution of key climate variables in the modelled current (full lines) and future (dashed lines) time periods. The six climate models are shown in different colours. log values for daily precipitation and snowfall are shown.

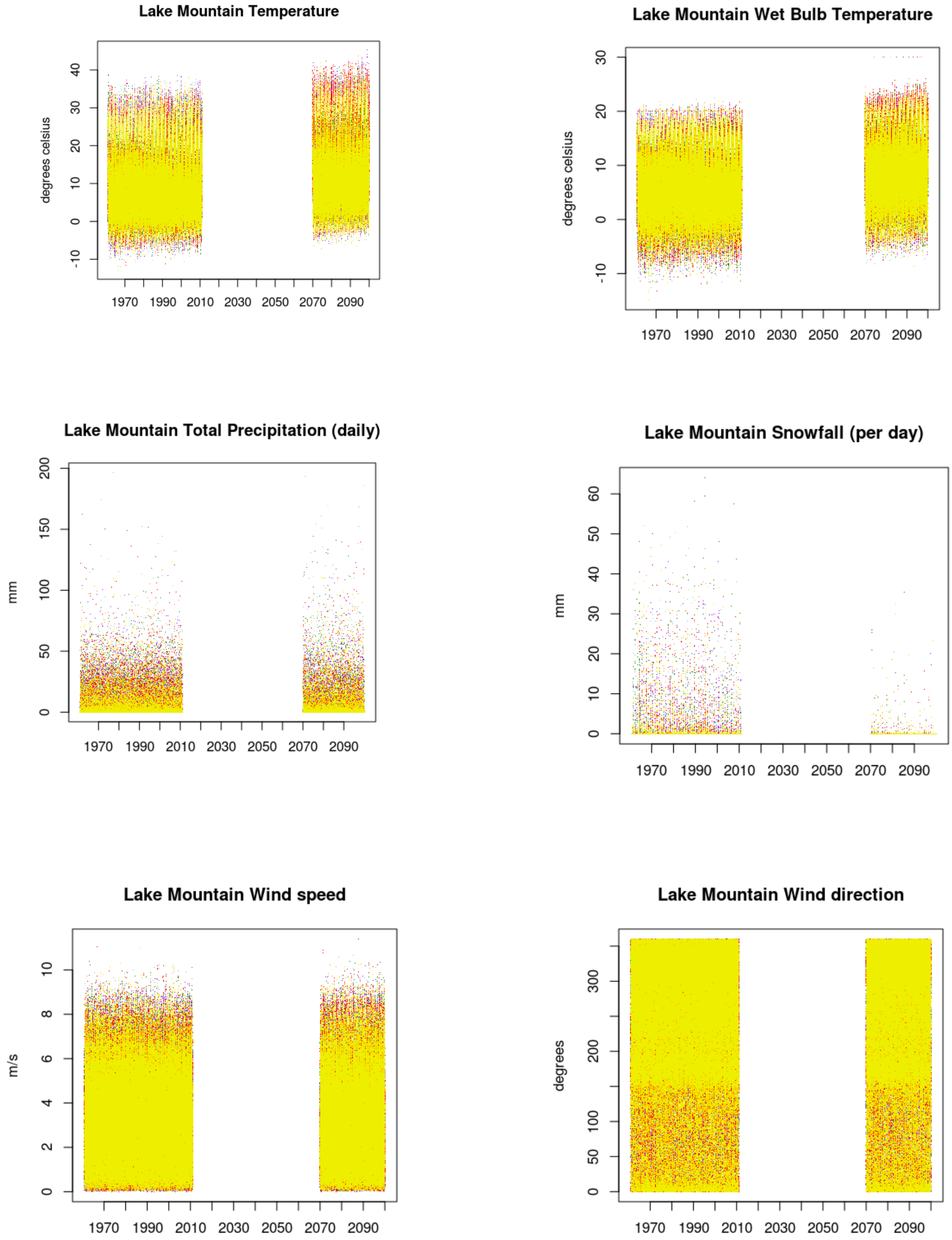


Figure 4.2E: Daily values of key climate variables from the six climate models showing the modelled periods, 1961-2010 and 2070-2099.

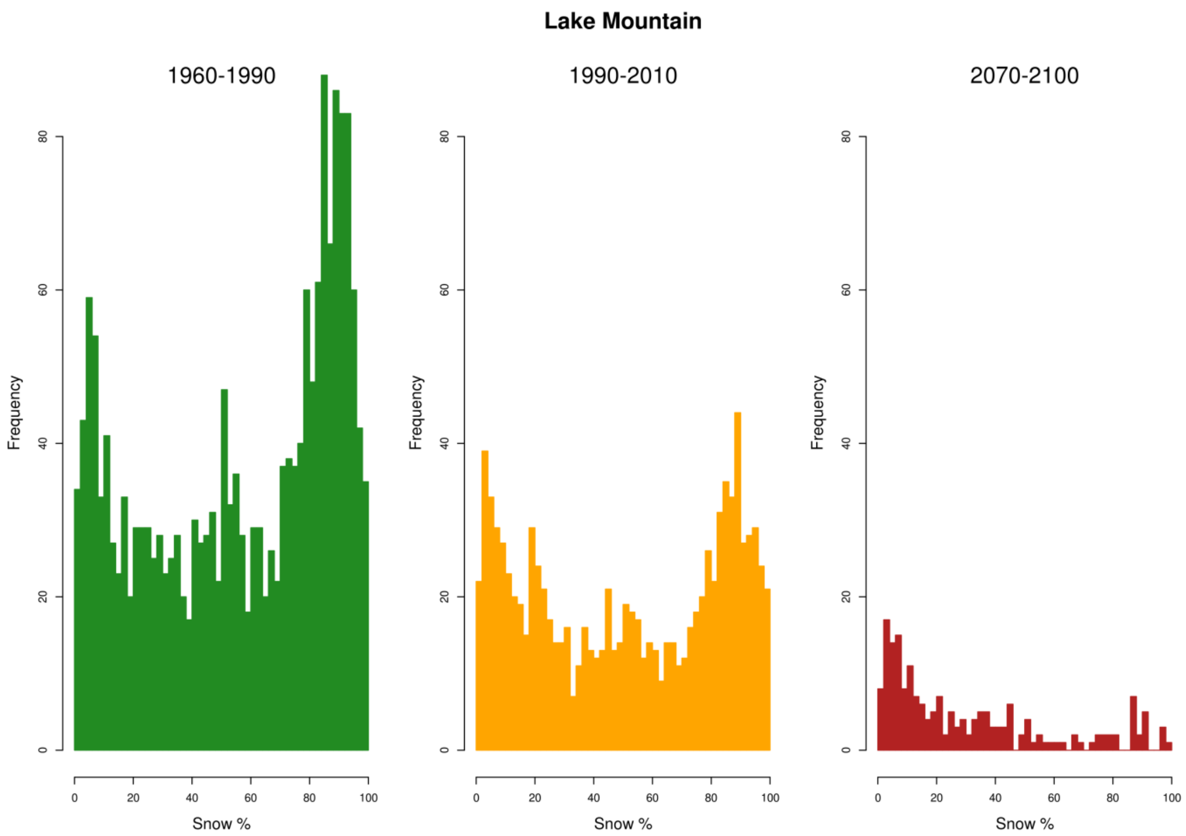
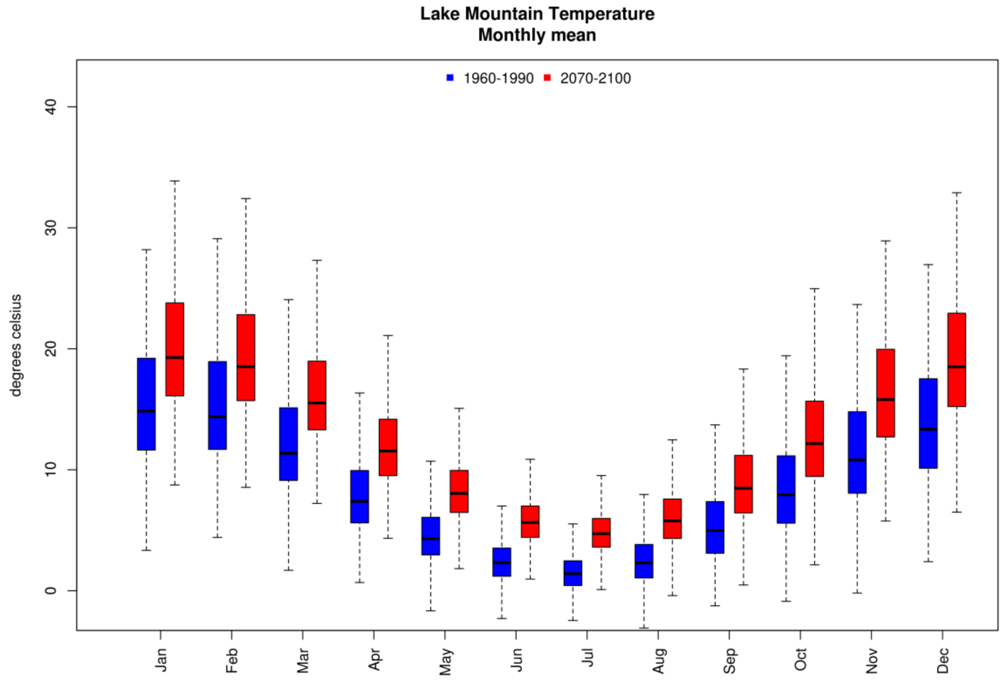
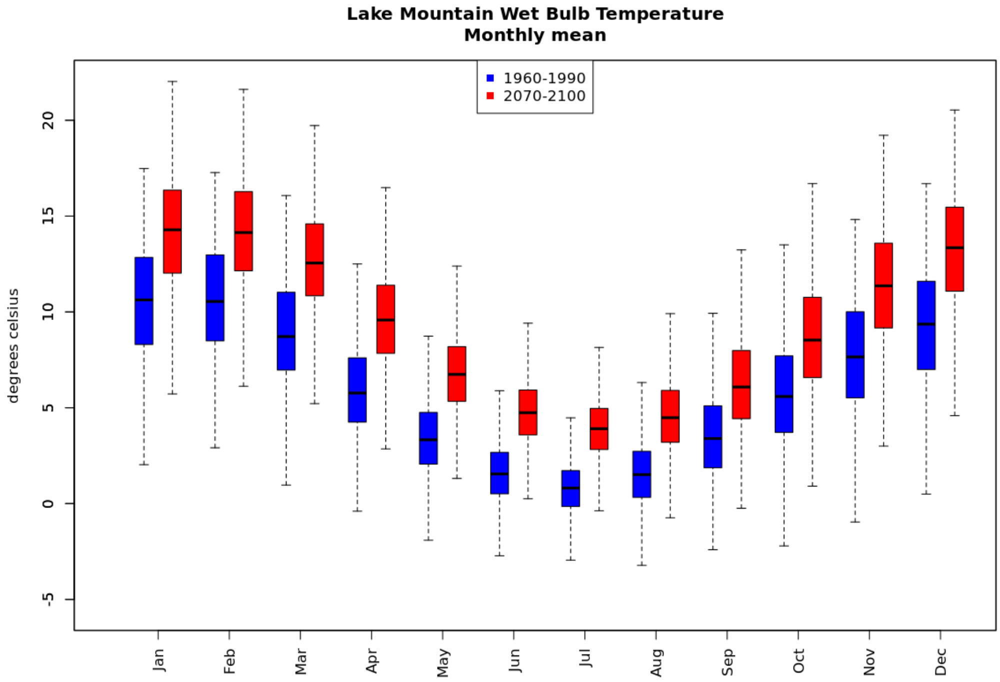
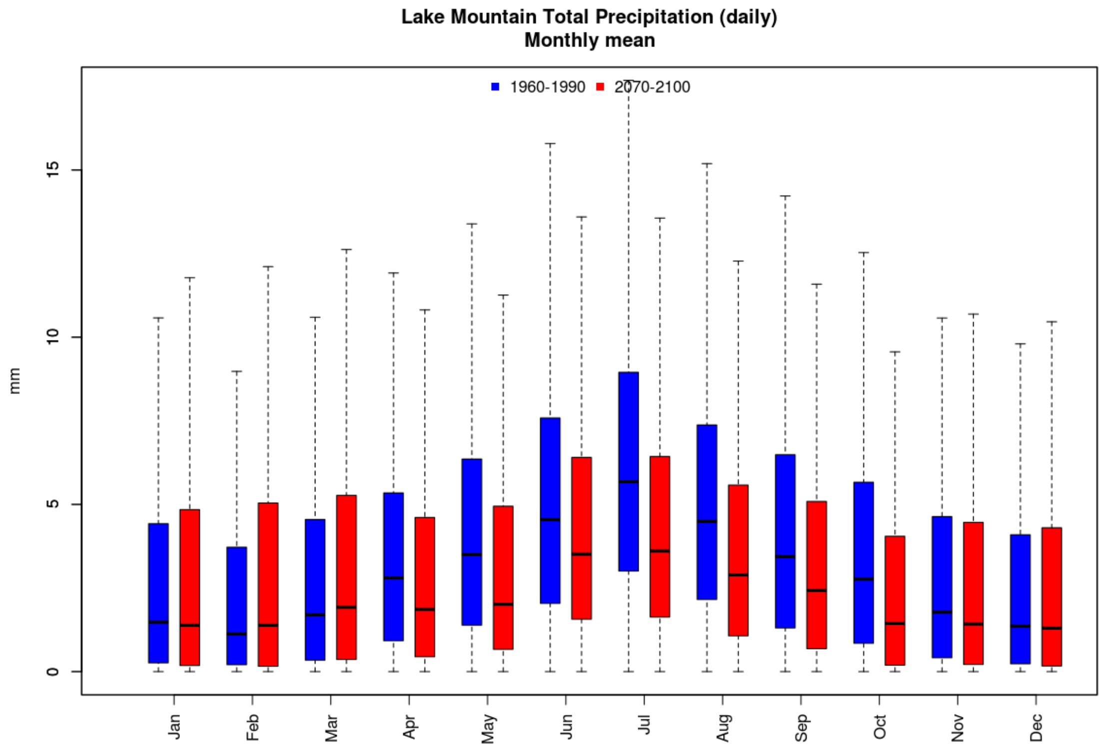


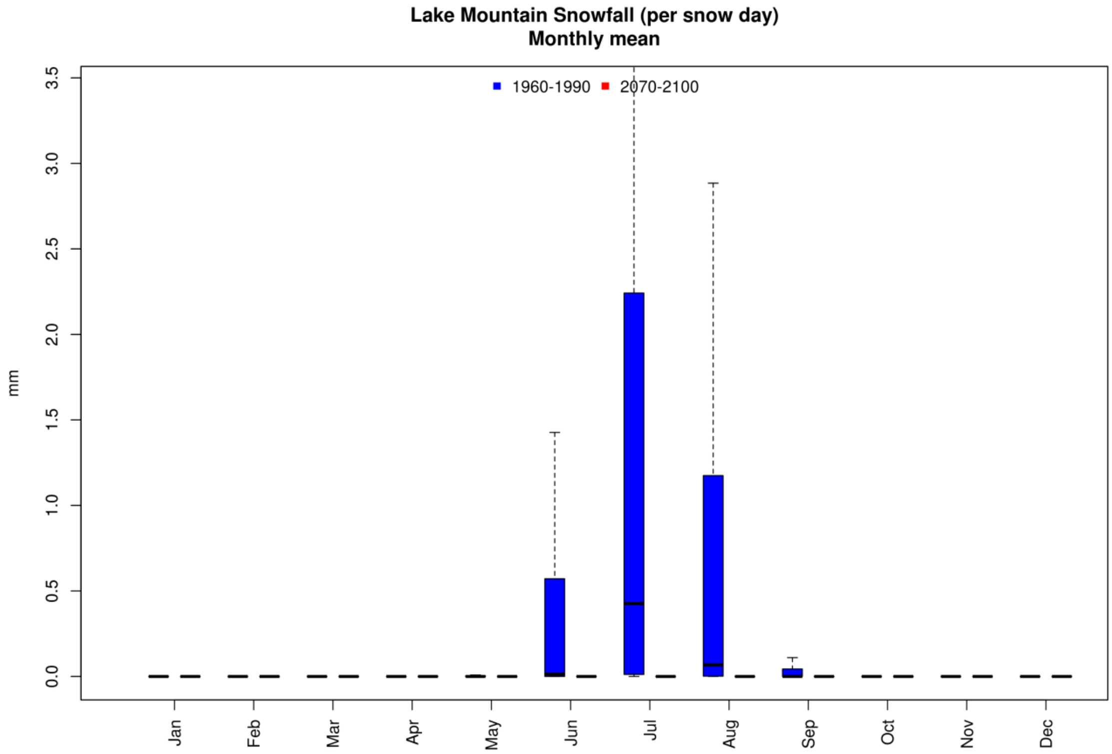
Figure 4.3E: The proportion of precipitation falling as snow in the historical (1960-1990), current (1990-2010) and future (2070-2100) periods.

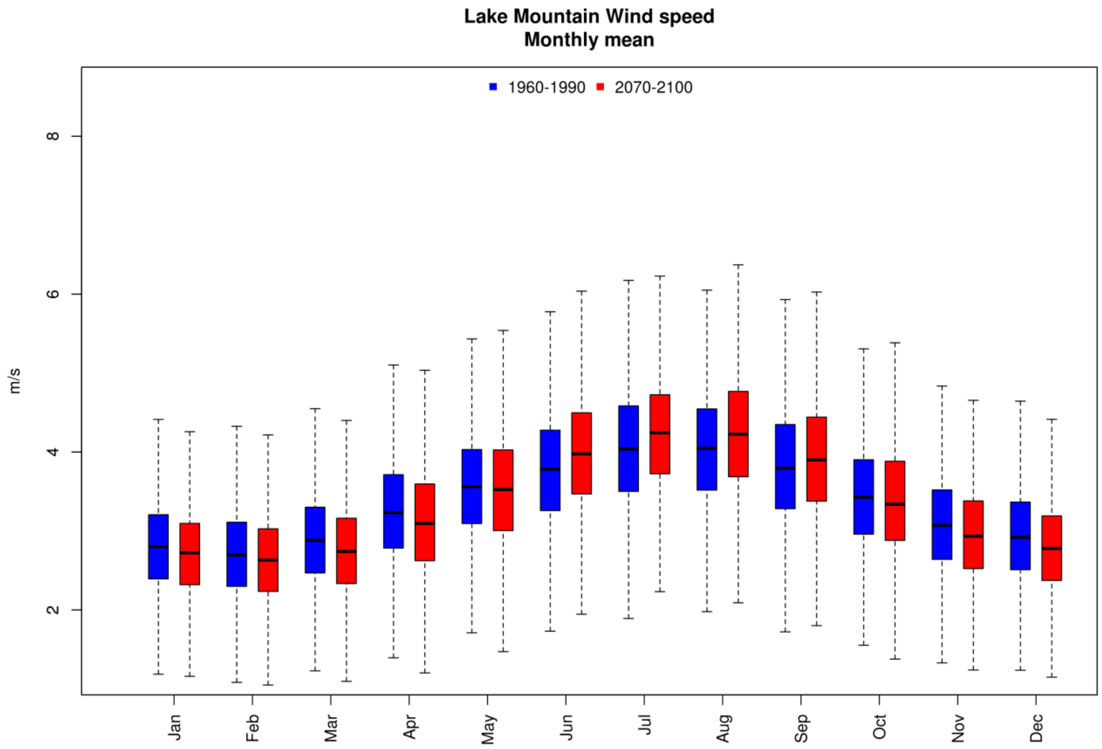

Lake Mountain Temperature
Monthly mean
1960-1990
2070-2100
degrees celsius
0
10
20
30
40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

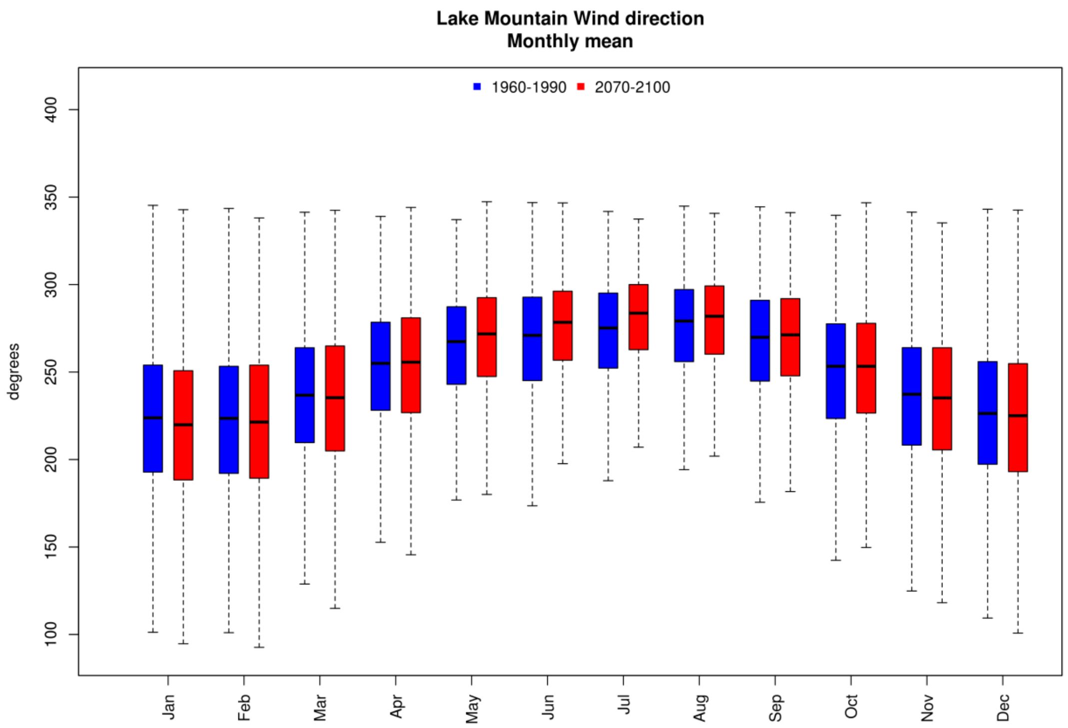

Lake Mountain Wet Bulb Temperature
Monthly mean
1960-1990
2070-2100
degrees celsius
-5
0
5
10
15
20
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

LAKE MOUNTAIN






Lake Mountain Wind speed
Monthly mean
1960-1990
2070-2100
m/s
2
4
6
8
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Lake Mountain Wind direction
Monthly mean
1960-1990
2070-2100
degrees
100
150
200
250
300
350
400
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

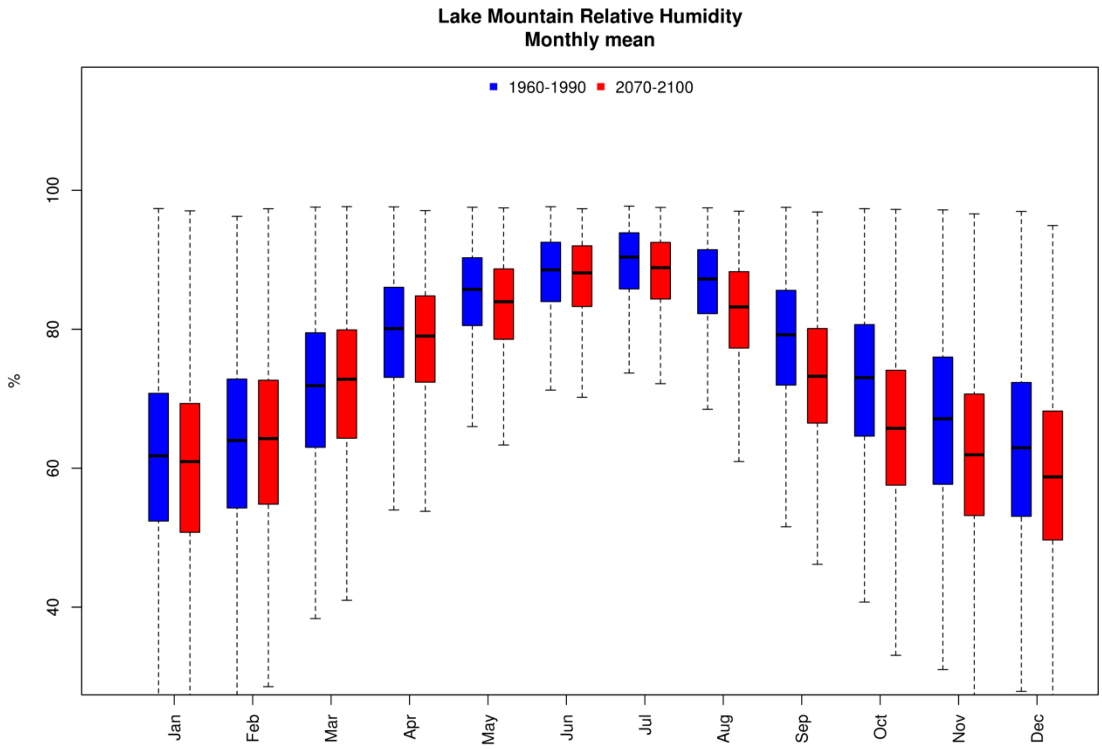


Figure 4.4E: The multi-model monthly mean values of key climate variables in the current (blue) and future (red) time periods. The bottom and top of the box are the 25th and 75th percentiles, the bar is the median, and the whiskers go to the most extreme data point which is no more than +/- 1.5 times the interquartile range from the box. Note that snowfall is the amount of snowfall on days when it snows.

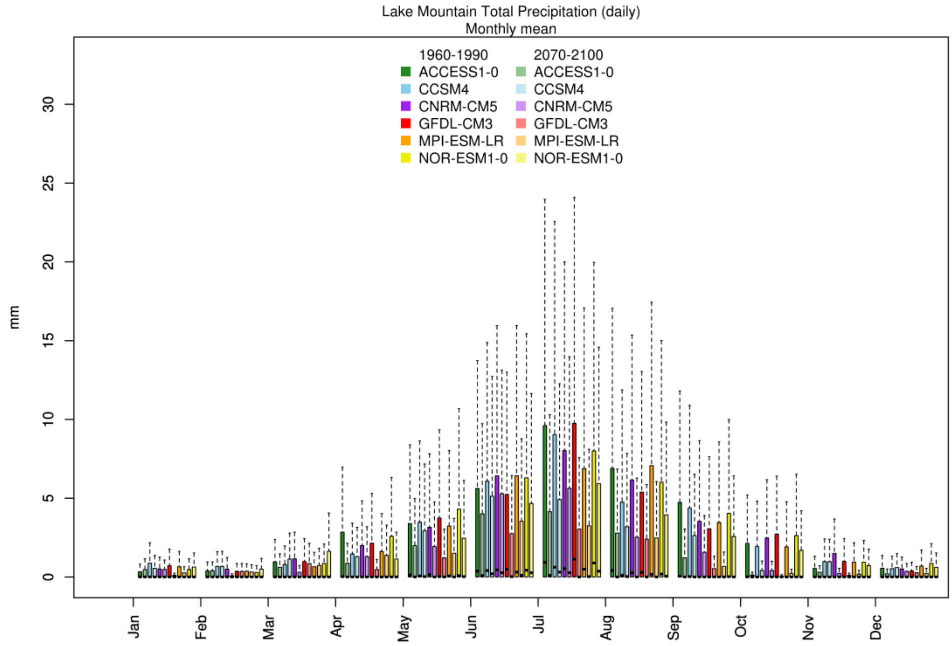


Figure 4.5E: The range in monthly mean precipitation projected by the six climate models in the current and future time periods.

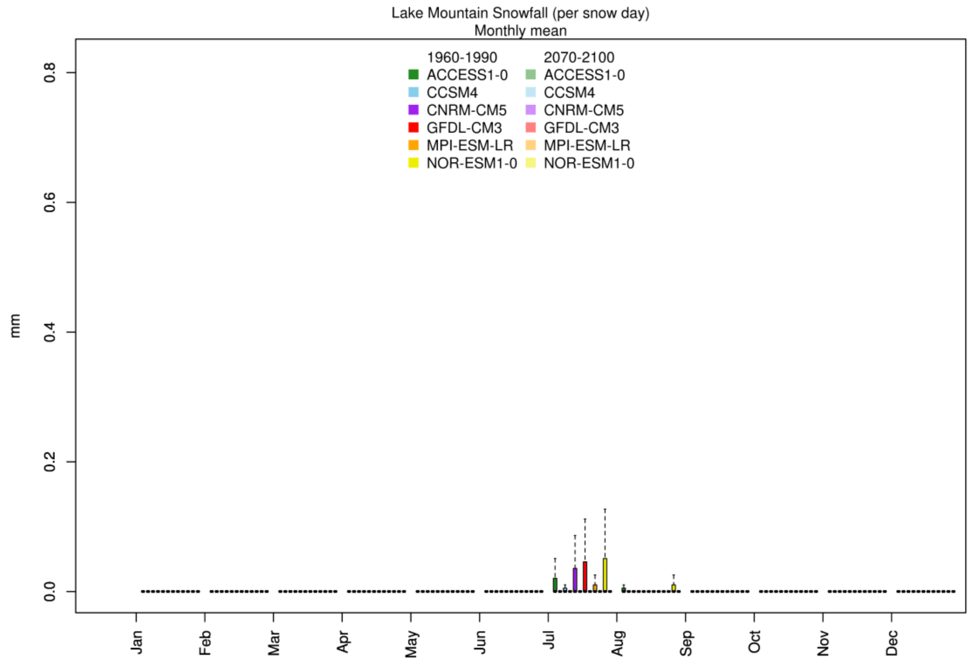


Figure 4.6E: The range in monthly mean snowfall projected by the six climate models in the current and future time periods.

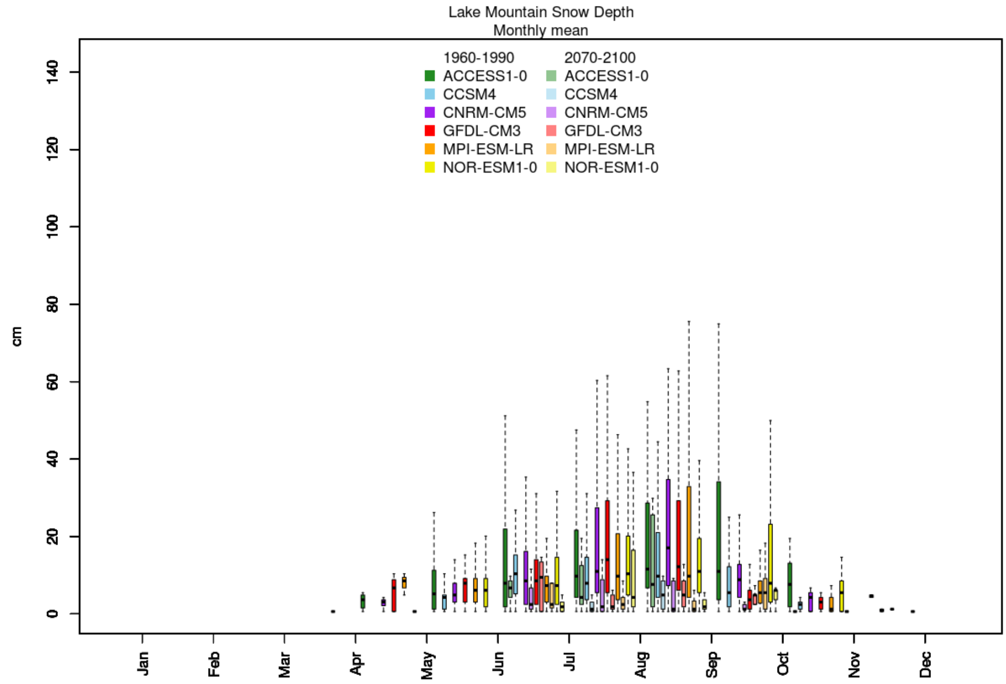


Figure 4.7E: The range in monthly mean snow depth projected by the six climate models in the current and future time periods.

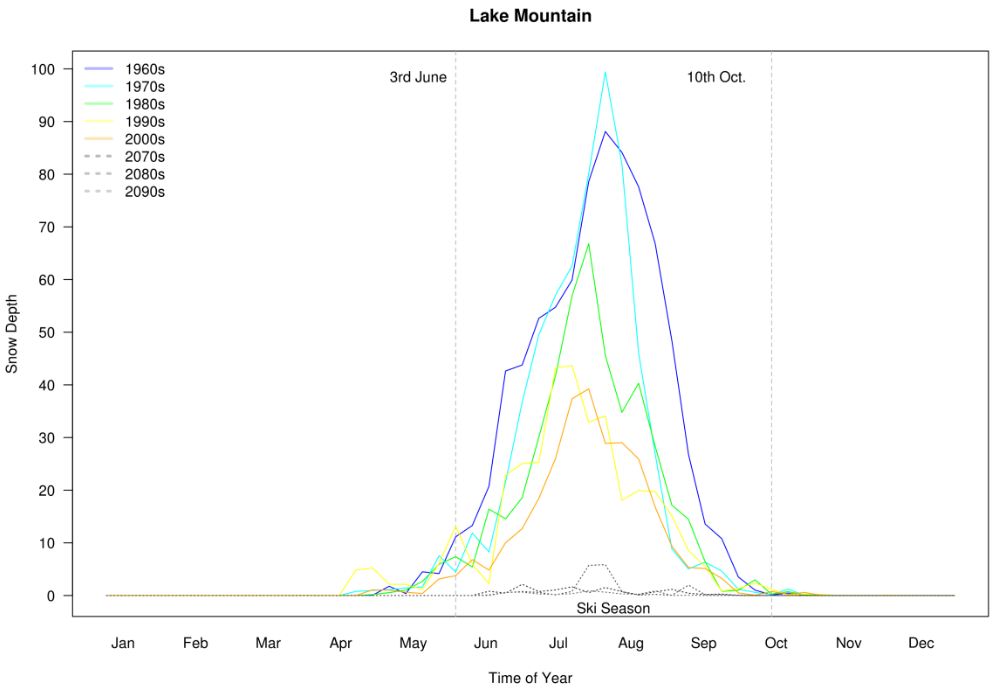


Figure 4.8E: The change in the ski season between current and future periods based on natural snow depth.

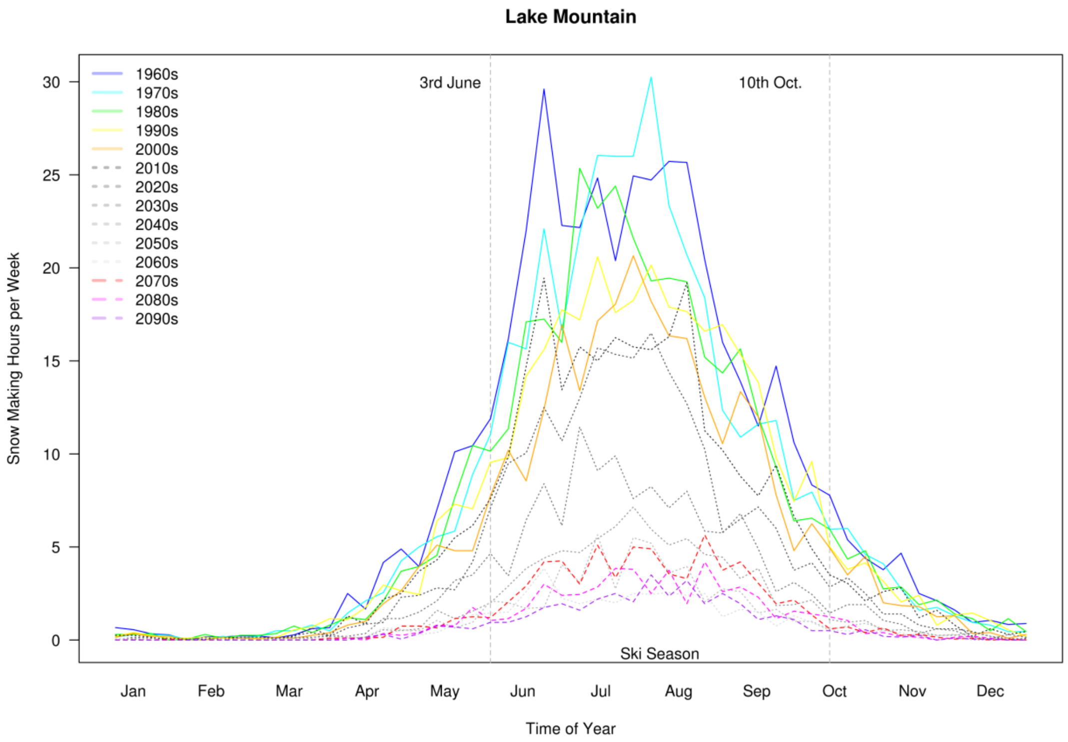
Table 4.2E: The number of snowmaking hours that accumulate at Lake Mountain by June 3rd based on three different thresholds for wet bulb temperatures (-2°C, -1°C, 0.5°C). Numbers in brackets show the range across the climate models. Values for the decades 1960-2010 and 2070-2090 are based on 3 hourly model output while the decades 2020-2060 are statistically derived.

Decade	Number of hours above Wet Bulb temperature threshold		
	-2°C	**-1°C**	**0.5°C**
1960s	61 (45 to 91)	121 (99 to 156)	286 (249 to 357)
1970s	51 (42 to 65)	102 (92 to 121)	252 (242 to 276)
1980s	49 (40 to 56)	104 (89 to 112)	248 (224 to 266)
1990s	45 (32 to 69)	91 (70 to 118)	217 (196 to 237)
2000s	35 (25 to 49)	74 (53 to 97)	193 (161 to 229)
2010s	36 (24 to 43)	78 (60 to 92)	204 (176 to 227)
2020s	25 (19 to 33)	55 (49 to 69)	159 (148 to 170)
2030s	19 (8 to 28)	42 (26 to 52)	122 (88 to 140)
2040s	9 (6 to 13)	22 (13 to 37)	77 (61 to 101)
2050s	7 (5 to 9)	16 (11 to 22)	55 (38 to 70)
2060s	6 (4 to 9)	14 (12 to 17)	51 (34 to 61)
2070s	6 (5 to 8)	17 (14 to 20)	55 (44 to 65)
2080s	5 (2 to 11)	13 (4 to 27)	42 (22 to 69)
2090s	4 (2 to 6)	10 (7 to 14)	34 (24 to 43)

Table 4.3E: Shift in ski season start date at Lake Mountain for three different thresholds for wet bulb temperatures (-2°C, -1°C, 0.5°C). Numbers in brackets show the range across the climate models. Values for the decades 1960-2010 and 2070-2090 are based on 3 hourly model output while the decades 2020-2060 are statistically derived. NA indicates that the season start date shifts to after the end of the current season (10th October).

Decade	Shift in season start date relative to the 1960's (Days)		
	-2°C	**-1°C**	**0.5°C**
1970s	0 (0 to 0)	0 (0 to 0)	0 (0 to 0)
1980s	4 (0 to 12)	4 (0 to 9)	4 (0 to 9)
1990s	7 (2 to 15)	5 (3 to 9)	6 (5 to 10)
2000s	9 (8 to 12)	10 (8 to 12)	10 (8 to 17)
2010s	17 (15 to 24)	16 (18 to 19)	15 (15 to 18)
2020s	13 (13 to 20)	13 (13 to 17)	13 (12 to 18)
2030s	23 (25 to 34)	24 (23 to 29)	21 (19 to 28)
2040s	38 (42 to 51)	36 (43 to 39)	33 (36 to 38)
2050s	72 (76 to 93)	68 (76 to 71)	56 (64 to 63)
2060s	149 (92 to NA)	105 (87 to NA)	79 (78 to 95)
2070s	NA (NA to NA)	NA (NA to NA)	95 (109 to 88)
2080s	96 (106 to 116)	82 (95 to 83)	67 (69 to 70)
2090s	NA (NA to NA)	114 (NA to 89)	80 (113 to 69)

a)



b)

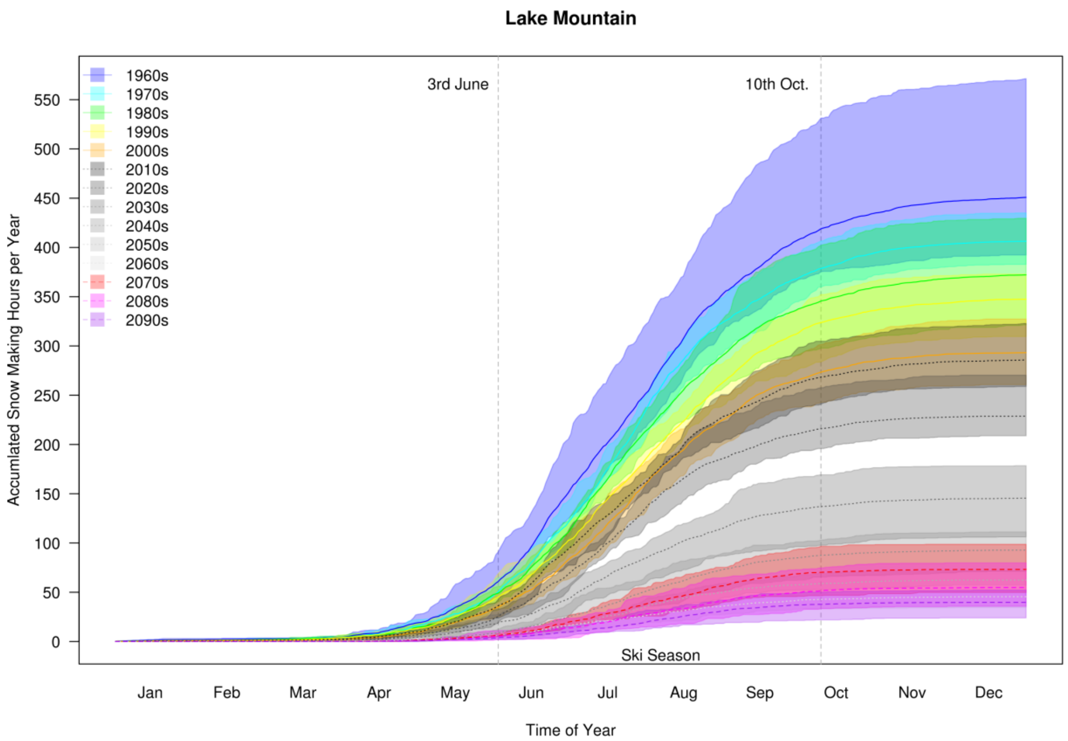
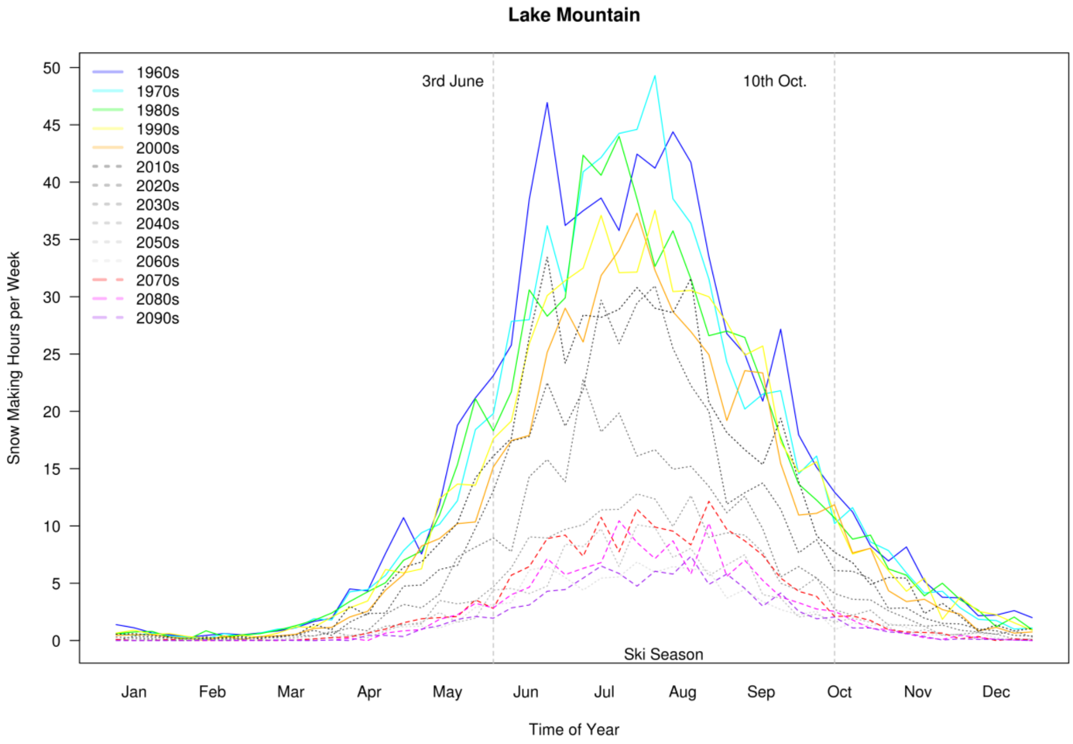


Figure 4.9E: The change in the number of hours suitable for snowmaking between current and future periods based on a threshold of -2°C wet bulb temperature. a) The number of hours per week below the threshold, b) Accumulated snowmaking hours per year

a)



b)

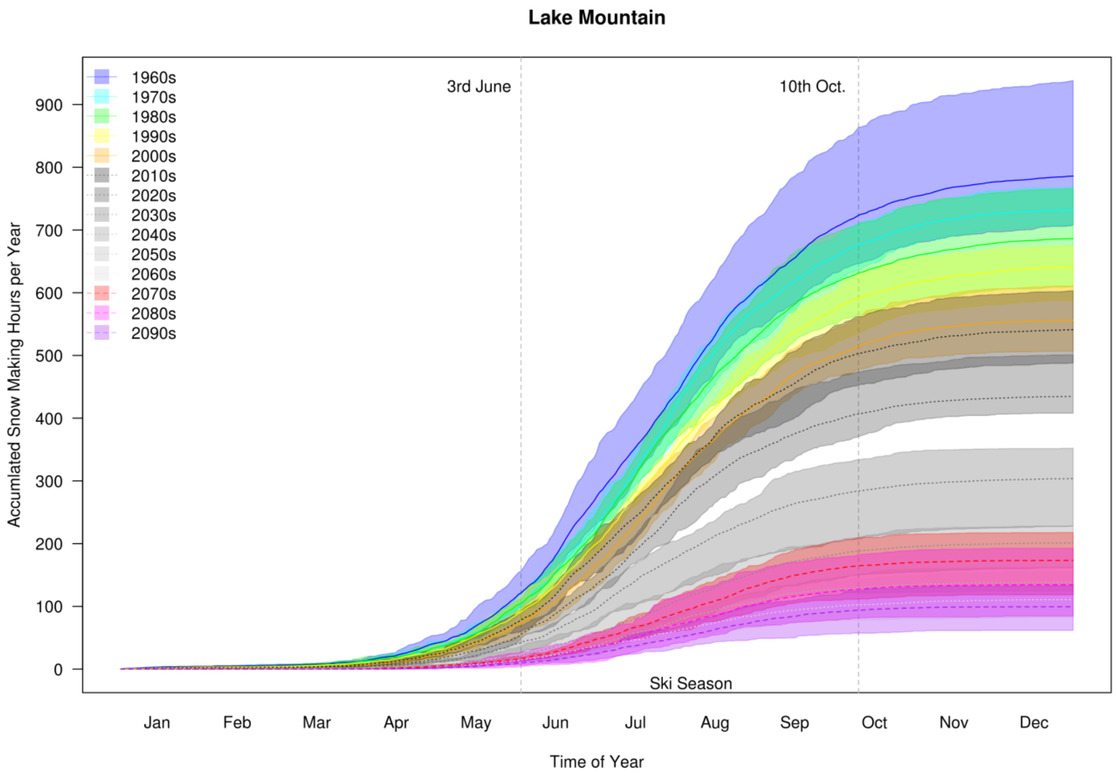
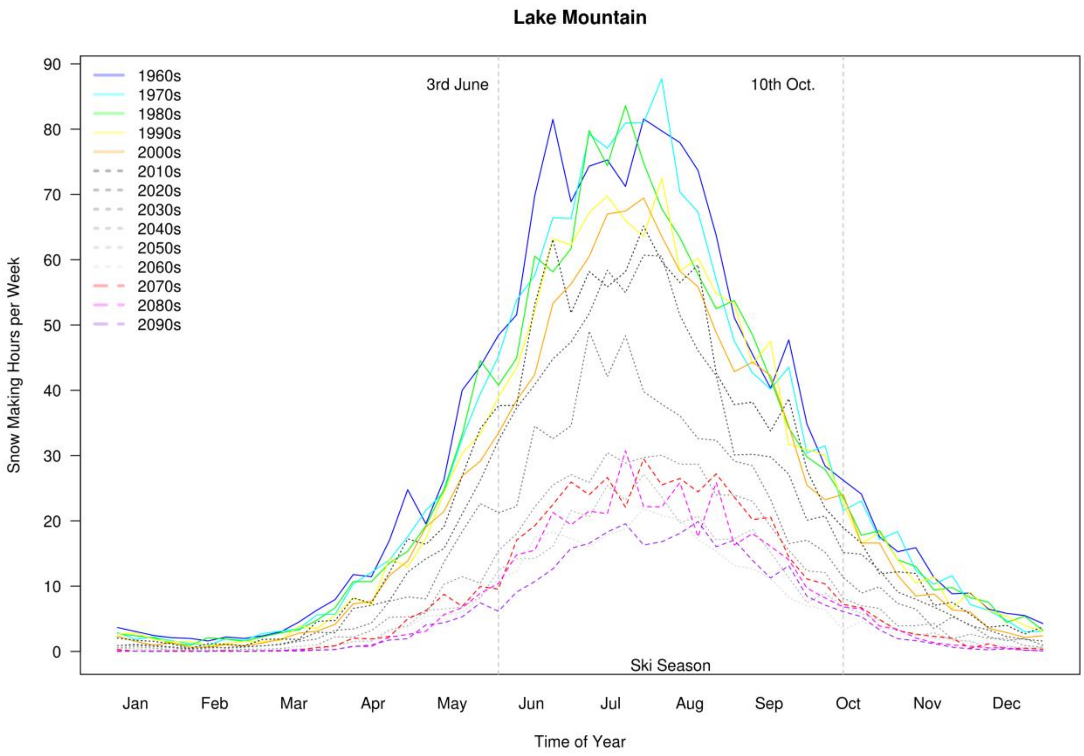


Figure 4.10E: The change in the number of hours suitable for snowmaking between current and future periods based on a threshold of -1°C wet bulb temperature. a) The number of hours per week below the threshold, b) Accumulated snowmaking hours per year

a)



b)

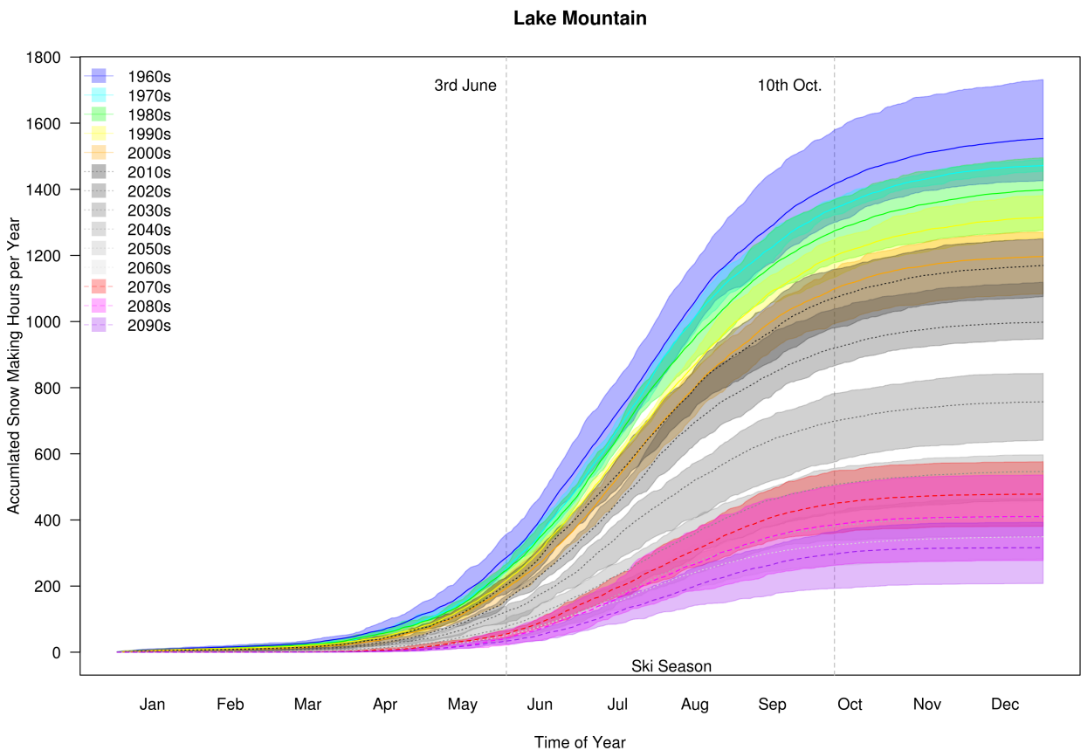


Figure 4.11E: The change in the number of hours suitable for snowmaking between current and future periods based on a threshold of 0.5°C wet bulb temperature. a) The number of hours per week below the threshold, b) Accumulated snowmaking hours per year

F. MT STIRLING (elevation 1749m)

This section describes the changes in climate that are projected to occur at the Mt Stirling resort. An explanation of the Climate Futures for the Australian Alps projections, the methods used and results from across all of the Victorian Alpine resorts can be found in the main report. The main report also provides important information about the scope of the study and considers the uncertainty associated with projections of future climate.

Relative to recent decades (1961-2010), the projections for Mt Stirling by the end of the century, under a high emissions scenario, show:

1. An increase in mean annual temperature of 3-5°C (mean of 4°C);
2. An increase in the number of extreme hot temperatures and a decrease in the number of very cold days;
3. The temperature of the coldest days in winter increases by approximately 3°C, while the temperature of the hottest summer days increase by approximately 5°C;
4. A mean decrease in annual precipitation of 7%. However, a maximum decrease of 13% to an increase of +6% is shown across the six climate models;
5. A decrease in precipitation from May through to September for all climate models;
6. Substantial reductions in snowfall, from 86% to 67% less snowfall than the baseline period (mean reduction of 74%);
7. With warmer temperatures there is a reduction in the proportion of precipitation falling as snow. More snow falling as sleet has implications for the retention of snow;
8. No change in wind speed or wind direction.

F1 Changes between current and future periods

The changes projected to occur at Mt Stirling between the current (1961-2010) and future (2070-2099) time periods are shown in Table 4.1F.

Figure 4.1F shows the frequency distribution for key climate variables in the modelled current (1961-2010) and future (2069-2099) time periods. The number of occurrences of a particular value is used to highlight any shifts in the overall distribution, the mean or the variance (spread) of the values for each climate variable. The shape of the distribution of temperatures (wet and dry bulb) does not change, but there is a shift towards higher temperatures across the distribution. There is an increase in the number of extreme hot temperatures and a decrease in the number of very cold days.

The daily values across all models are shown in Figure 4.2F.

The proportion of precipitation falling as snow in the historical, current and future periods are shown in Figure 4.3F. Fewer snow days in the future means that there will be fewer days when precipitation is 100% snow. There is also a reduction in the proportion of snow, with more snow falling as sleet. This has implications for the retention of natural or artificial snow.

F2 Changes to monthly mean values

A comparison of the multi-model mean monthly values of key climate variables in the current and future time periods is presented in Figure 4.4F. Increases in temperature are evident in every month of the year. In the future, the monthly mean temperature of the winter months, (June, July and August) is projected to be more like that currently experienced in autumn and spring. Temperatures in June, July and August in the future are projected to be similar to those currently experienced in May or September. May and September in the future period show temperatures similar to those currently experienced in April or October. This could potentially affect the ability for artificial snow to be laid down in the months leading up to the ski season.

Similarly, mean monthly wet bulb temperatures increase in all months, and show the same shifts in winter towards temperatures currently more typical of autumn and spring. Wet bulb temperature does not increase as much as dry bulb temperature, however, because wet bulb temperature reflects the influence of humidity, which is not projected to change substantially in the future. Note that this summary of monthly values does not show the very low temperatures because it is based on daily means.

There are no changes to wind speed or direction in any month of the year. Projections of humidity, however, which showed no change in annual means, is projected to decrease slightly in the months from April to August, with more substantial reductions evident from August to December (Figure 4.4F).

The large range in monthly values for precipitation are due to the range in values across the six climate models (Table 4.1F). However, all models project decreased precipitation to occur during the months May through to September (Figure 4.5F). In the other months, there is more inconsistency in the direction of change, with some models showing slight increases and others decreases. While there are no changes to the proportion of precipitation falling as snow, substantial reductions in snowfall and snow depth are projected by all climate models in all months (Figure 4.6F, Figure 4.7F). Not only are there fewer days when it snows, but there is reduced snowfall on days when it does snow.

F3 Shifts in the timing and duration of the ski season based on natural snow

The change in the duration and timing of the ski season between current and future periods based on natural snow depth is shown in Figure 4.8F.

There has been a steady reduction in snow depth over recent decades, from the 1960’s to 2010’s, and the duration of the ski season has contracted, with a later start and earlier finish. Assuming a depth of 30cm is required for skiing, the season length has contracted by 17% relative to the historical period (1960’s) in the model. Relative to the 2000-2010 period it is projected to contract by 87% by the 2070’s.

F4 Changes to the frequency of suitable snowmaking conditions

Mt Stirling is a cross-country skiing area, so does not have downhill runs or snowmaking. Results are therefore not presented here for the number of suitable snowmaking hours.

Table 4.1F: Projected change in key climate variables at Mt Stirling between the current (1961-2010) and future (2070-2099) time periods. The multi-model mean is shown for each 30 year period, with the range of change between climate models shown in brackets.

	Temperature (°C)			Wet bulb temperature (°C)			Precipitation (mm)		Snowfall (mm)		Wind speed (m/s)	Wind direction (m/s)
	Minimum Winter	Maximum Summer	Mean annual	Minimum Winter	Maximum Summer	Mean annual	Mean Daily	Mean Annual	Maximum weekly	Mean Annual Maximum	Mean annual	
Current	-3.83 (-3.96, -3.70)	27.06 (26.50, 27.59)	8.57 (8.43 , 8.69)	-14.19 (-17.86, -11.62)	21.26 (20.63, 21.62)	5.66 (5.58, 5.78)	3.66 (3.60, 3.72)	1335.9	8.39 (6.78, 9.93)	436.28	3.03 (3.01, 3.05)	232.59 (231.20, 234.36)
Future	-0.98 (-1.46, -0.51)	32.22 (30.12, 34.11)	12.74 (11.65, 13.81)	-9.32 (-10.71, -8.27)	30 (30, 30)	9.10 (8.62, 9.66)	3.39 (3.14, 3.93)	1237.35	2.19 (0.94, 3.28)	113.88	3.03 (2.96, 3.10)	231.79 (227.92, 234.95)
Change	2.85 (2.34, 3.44)	5.15 (3.13, 7.27)	4.17 (3.10, 5.38)	4.87 (2.64, 8.86)	8.74 (8.38, 9.37)	3.44 (2.98, 4.06)	-0.27 (-0.58, 0.33)	-7% (-13%, +6%)	-6.20 (-7.87, -4.15)	-74% (-86%,-67%)	0 (-0.07, 0.05)	-0.81 (-5.57, 3.42)

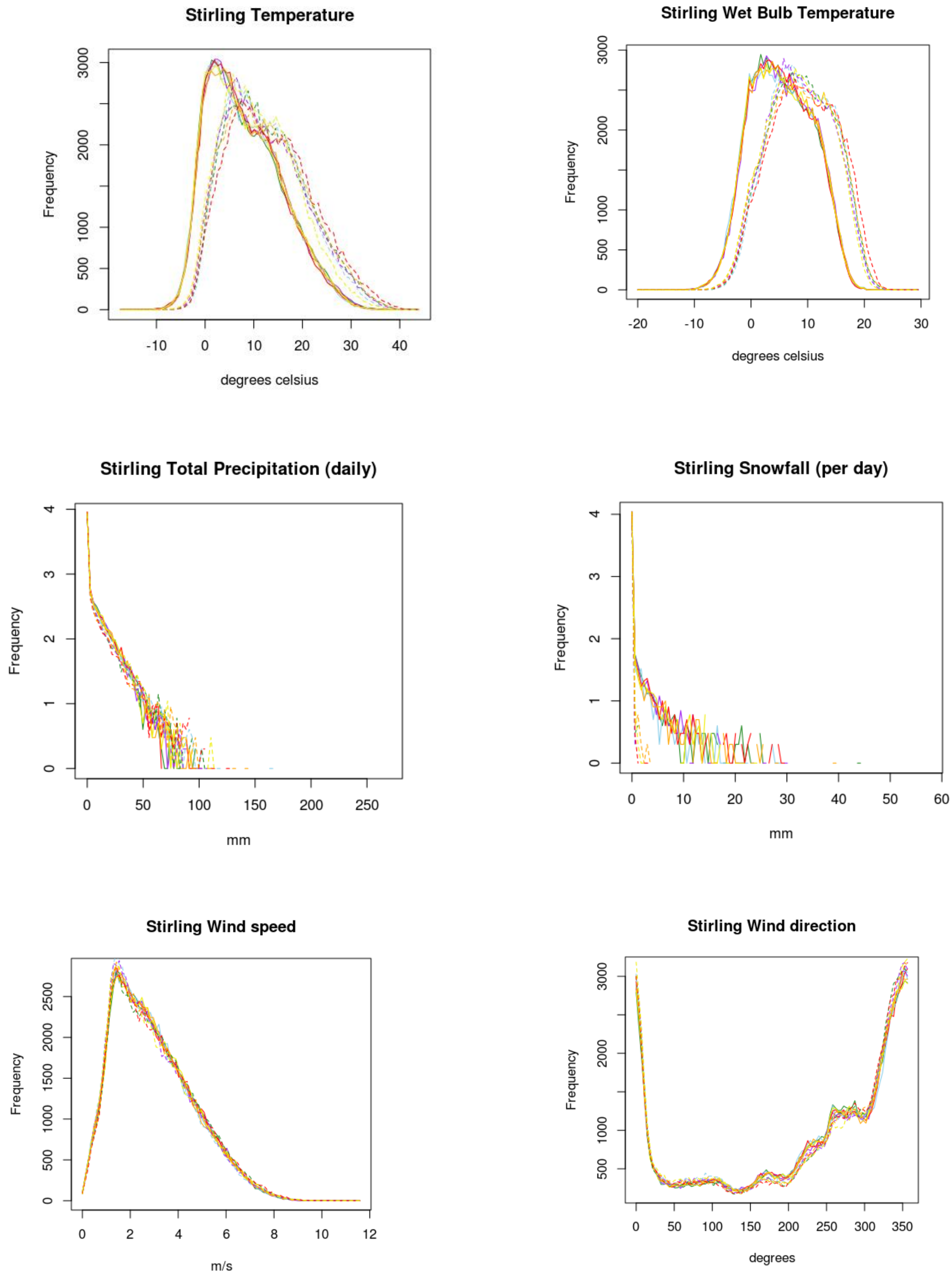


Figure 4.1F: Frequency distribution of key climate variables in the modelled current (full lines) and future (dashed lines) time periods. The six climate models are shown in different colours. log values for daily precipitation and snowfall are shown.

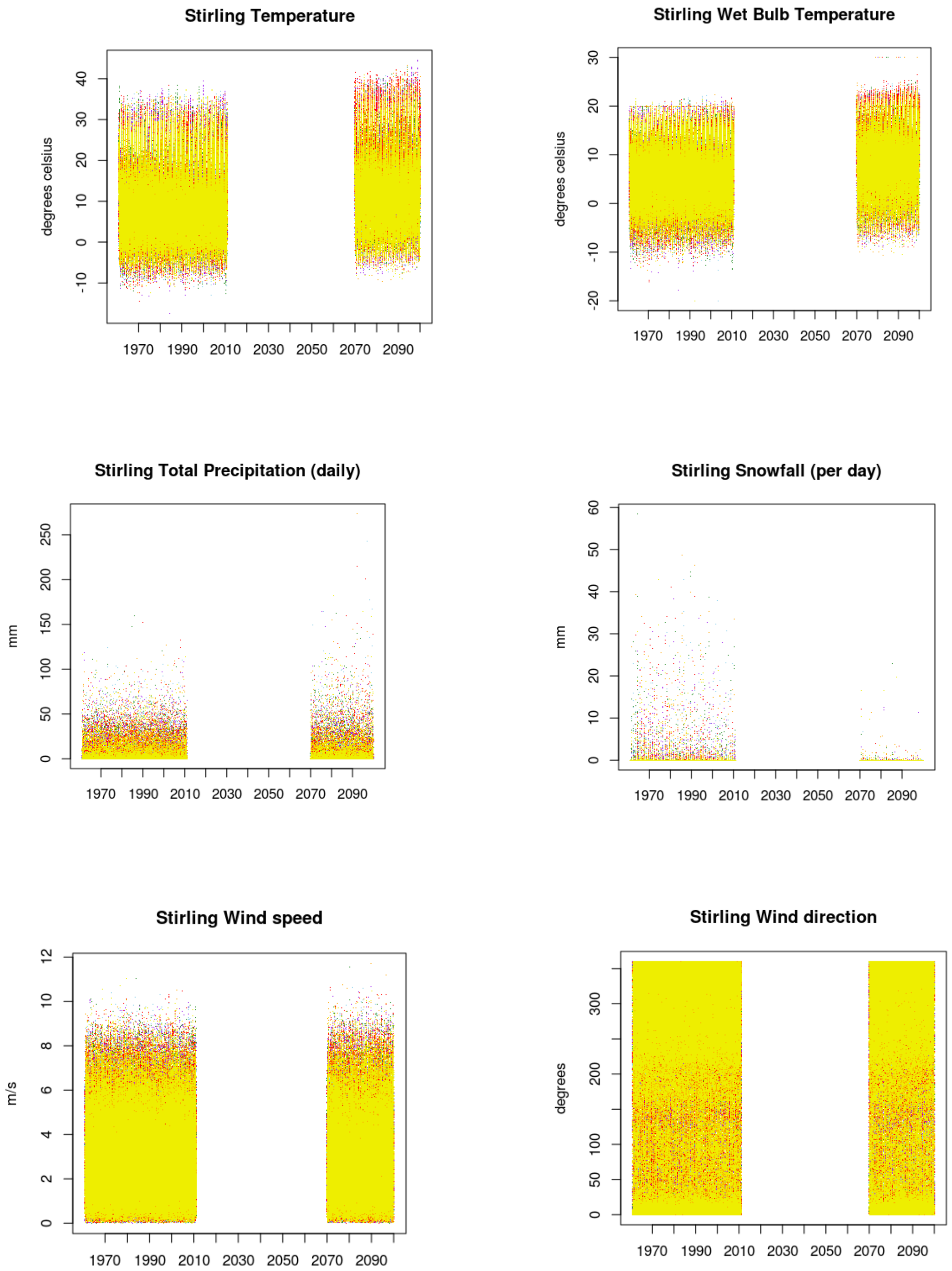


Figure 4.2F: Daily values of key climate variables from the six climate models showing the modelled periods, 1961-2010 and 2070-2099.

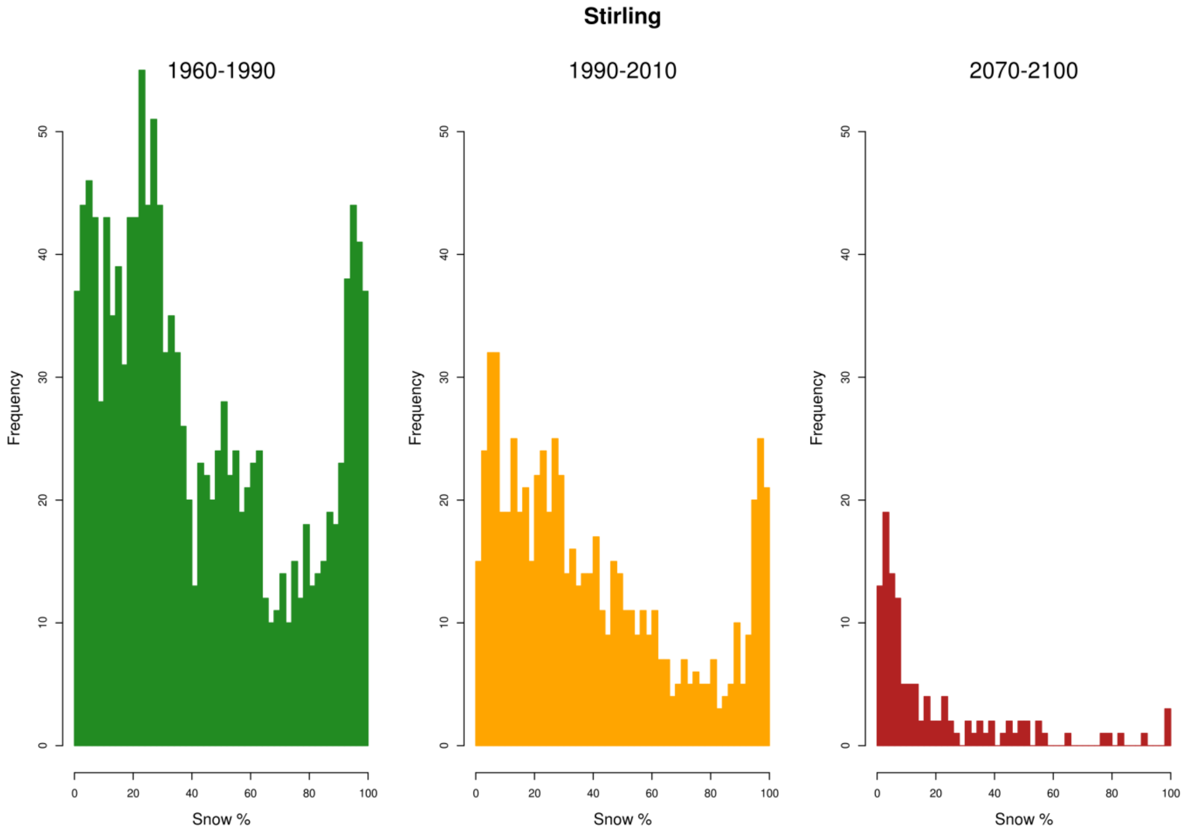
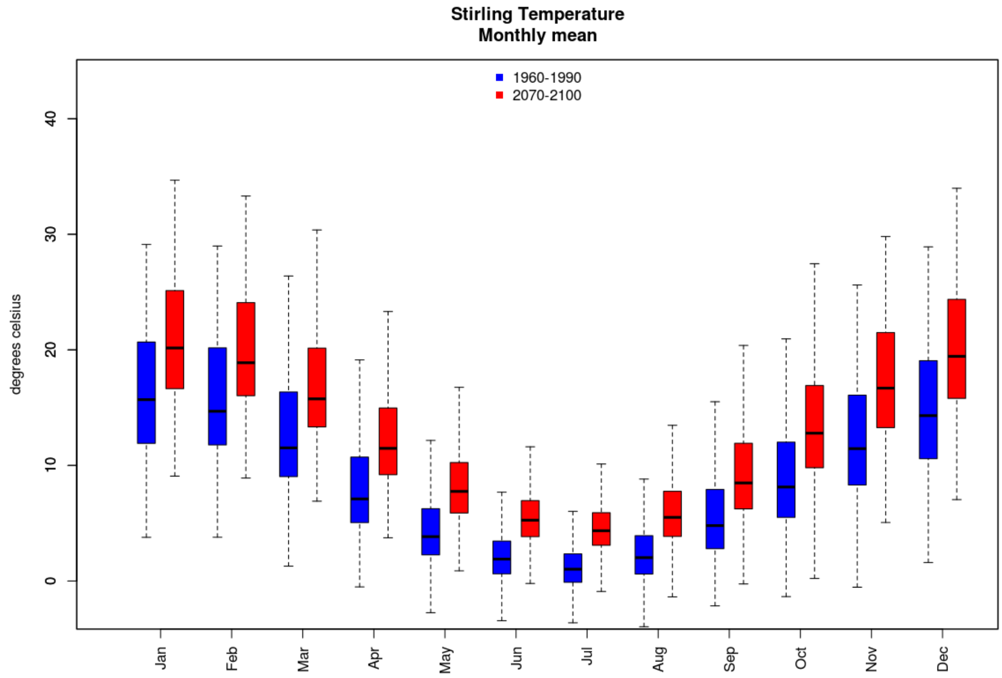
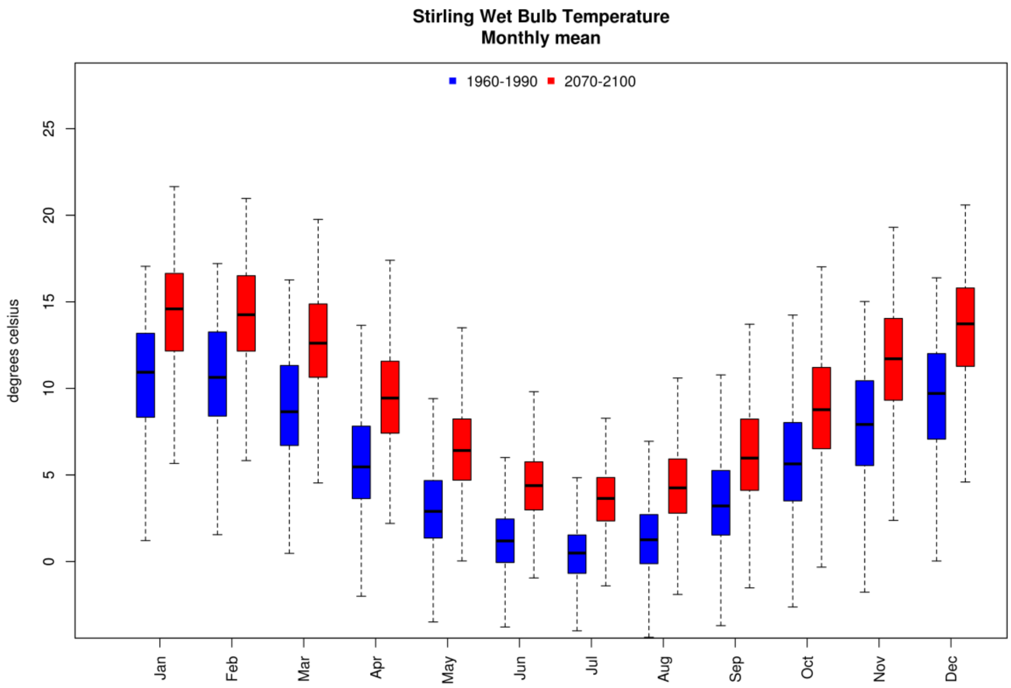
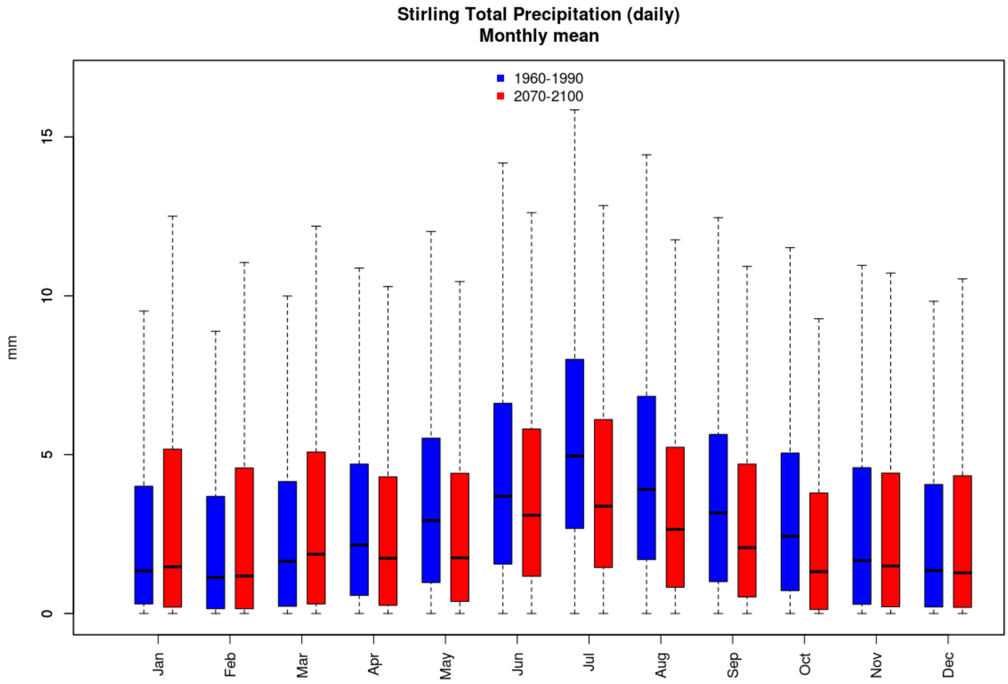
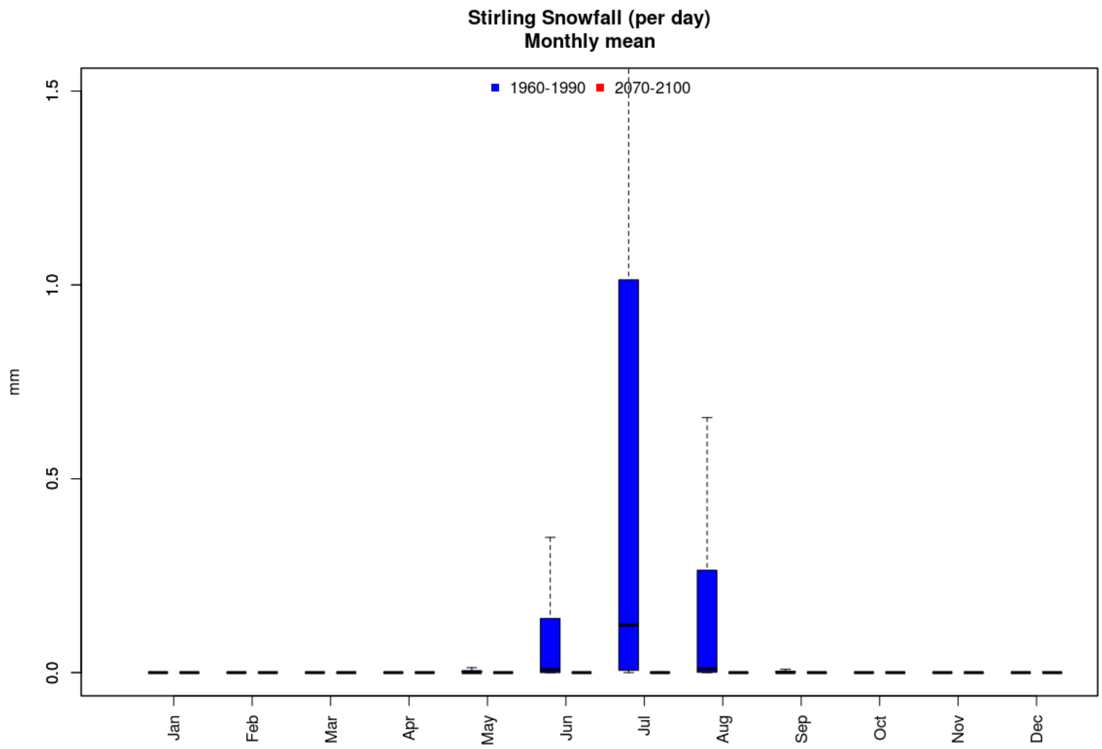


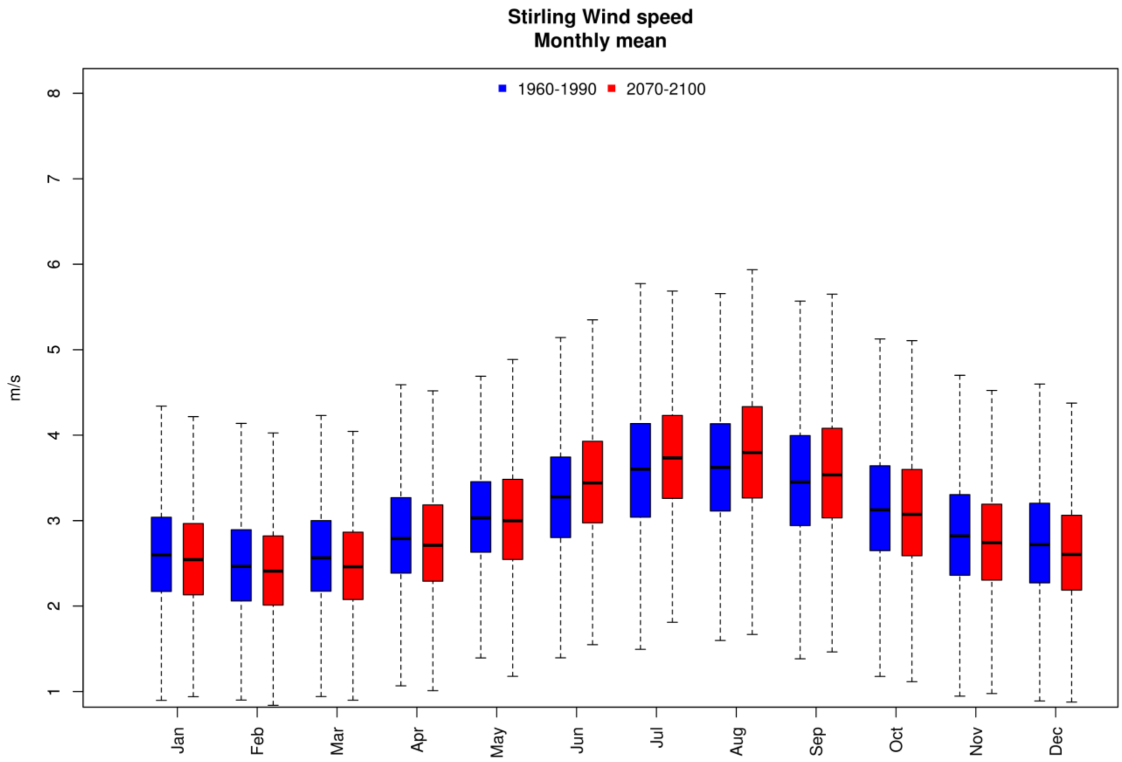
Figure 4.3F: The proportion of precipitation falling as snow in the historical (1960-1990), current (1990-2010) and future (2070-2100) periods.

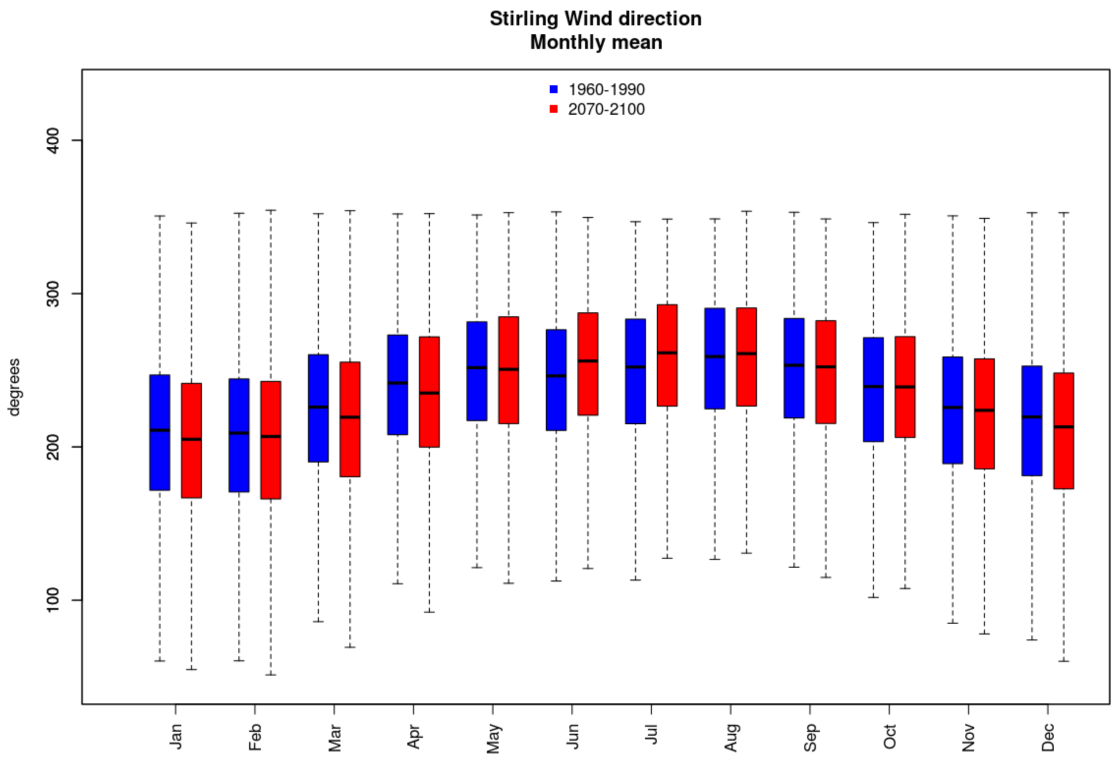

Stirling Temperature
Monthly mean
1960-1990
2070-2100
degrees celsius
0
10
20
30
40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Stirling Wet Bulb Temperature
Monthly mean
1960-1990
2070-2100
degrees celsius
0
5
10
15
20
25
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Stirling Total Precipitation (daily)
Monthly mean
1960-1990
2070-2100
mm
0
5
10
15
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Stirling Snowfall (per day)
Monthly mean
1960-1990
2070-2100
mm
0.0
0.5
1.0
1.5
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Stirling Wind speed
Monthly mean
1960-1990
2070-2100
m/s
1
2
3
4
5
6
7
8
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Stirling Wind direction
Monthly mean
1960-1990
2070-2100
degrees
100
200
300
400
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

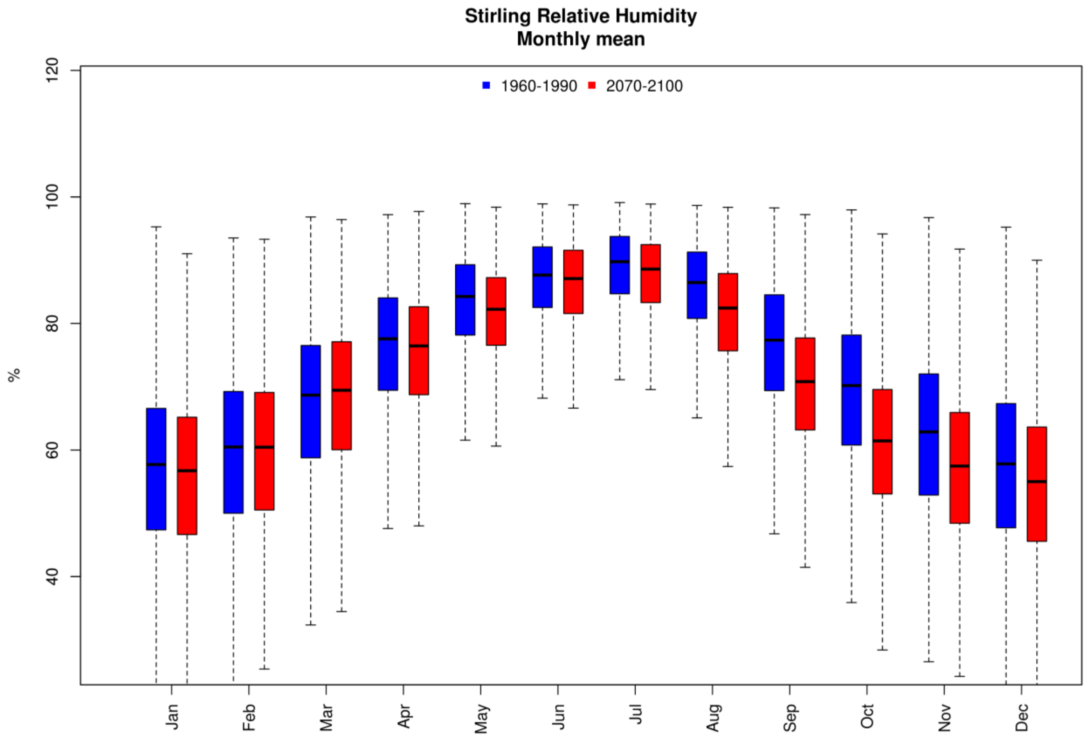


Figure 4.4F: The multi-model monthly mean values of key climate variables in the current (blue) and future (red) time periods. The bottom and top of the box are the 25th and 75th percentiles, the bar is the median, and the whiskers go to the most extreme data point which is no more than +/- 1.5 times the interquartile range from the box. Note that snowfall is the amount of snowfall on days when it snows.

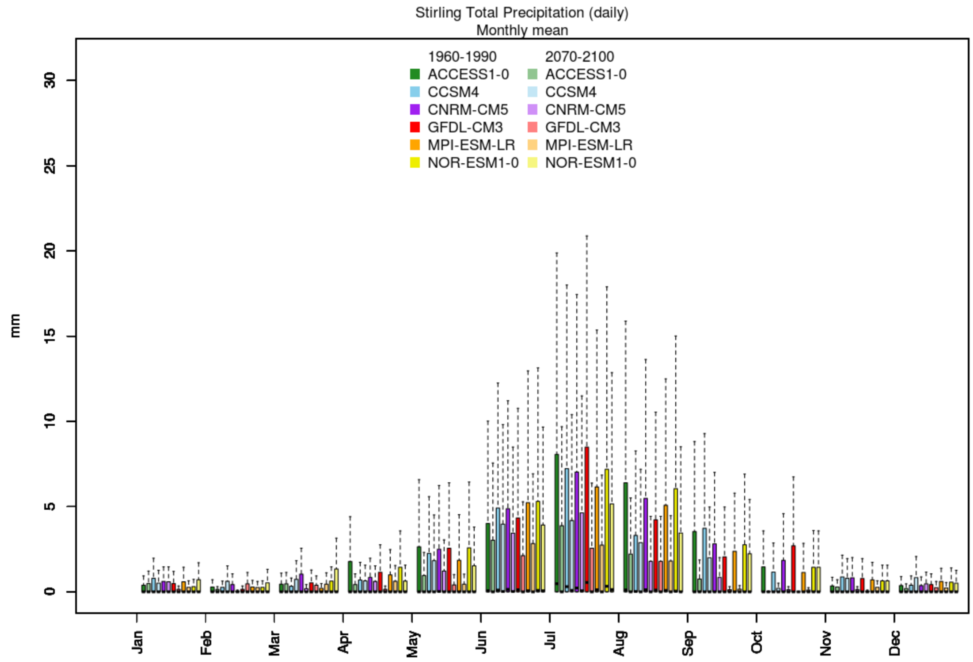


Figure 4.5F: The range in monthly mean precipitation projected by the six climate models in the current and future time periods.

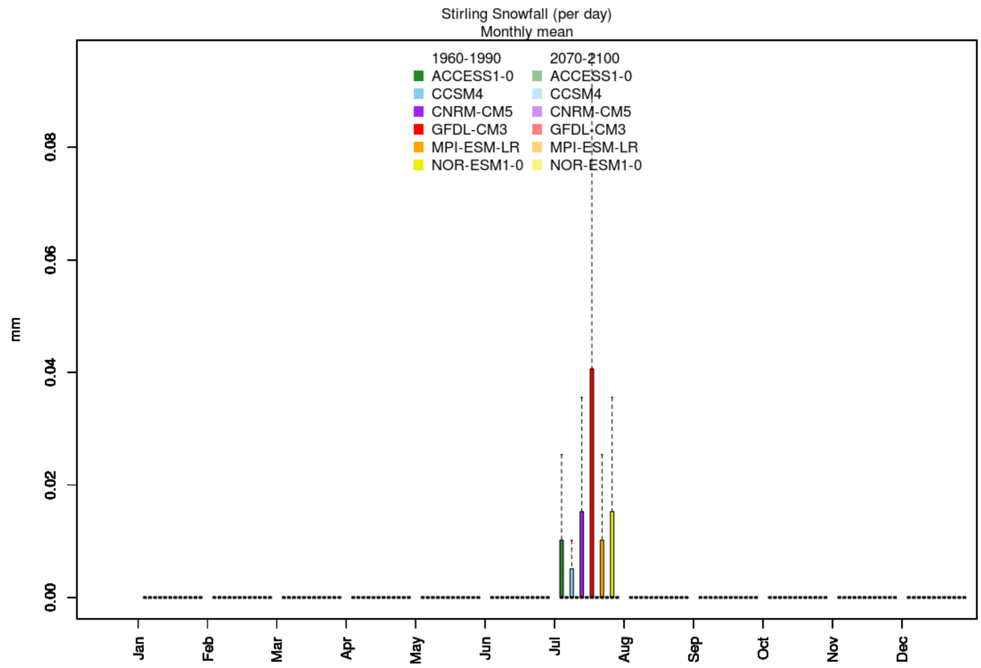


Figure 4.6F: The range in monthly mean snowfall projected by the six climate models in the current and future time periods.

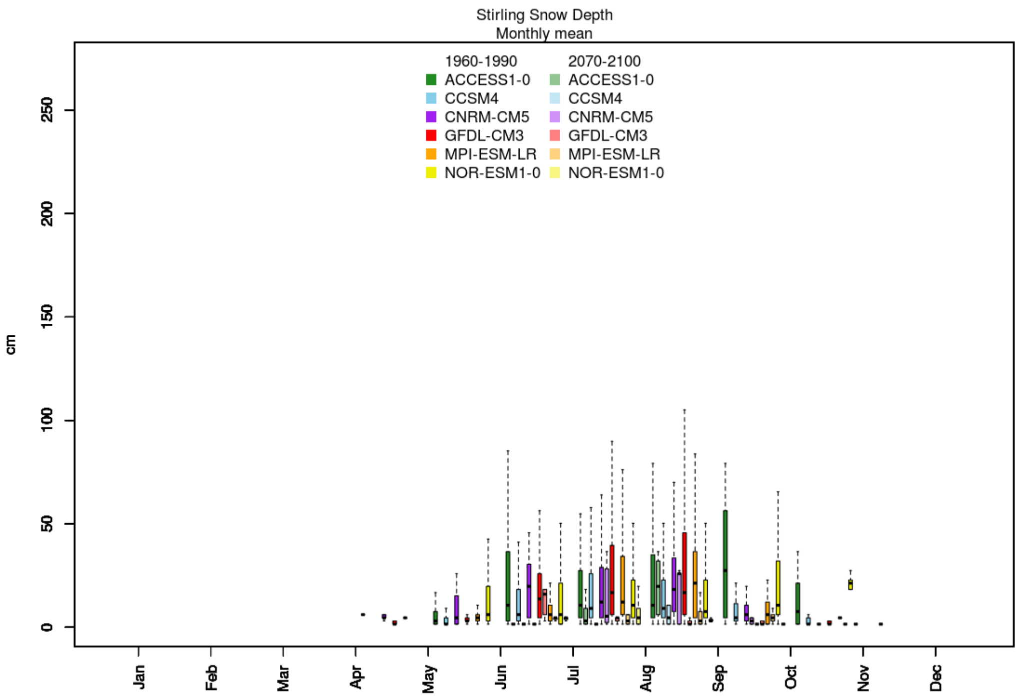


Figure 4.7F: The range in monthly mean snow depth projected by the six climate models in the current and future time periods.

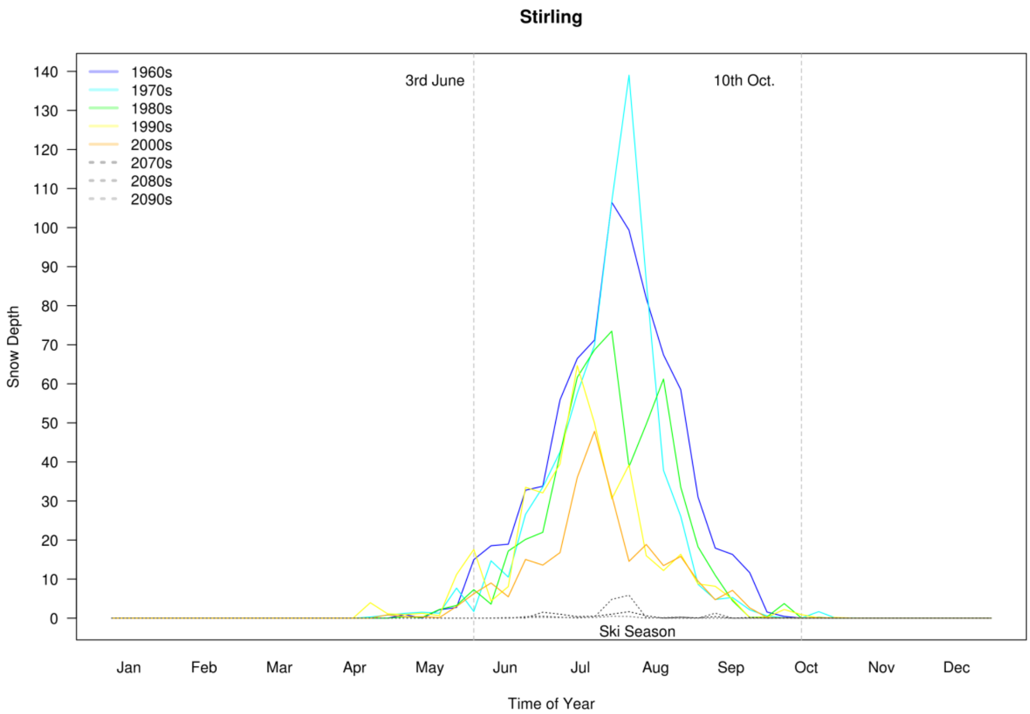


Figure 4.8F: The change in the ski season between current and future periods based on natural snow depth.