DEPARTMENT OF PLANNING, INDUSTRY & ENVIRONMENT

Climate change impacts in the NSW and ACT Alpine region

Projected changes in snowmaking conditions

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Cover photo: Winter landscape in Kosciuszko National Park. John Spencer/DPIE

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ACE CRC	Antarctic Climate & Ecosystems Cooperative Research Centre
ACT	Australian Capital Territory
CMIP	Coupled Model Intercomparison Project
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DPIE	Department of Planning, Industry and Environment
ECL	East Coast Low
GCM	Global Climate Model
MCAS-S	Multi-Criteria Analysis Shell for Spatial Decision Support
MM	Murray-Murrumbidgee state planning region
NARCliM	NSW/ACT Regional Climate Modelling project
NetCDF	Network Common Data Form
NSW	New South Wales
OEH	Office of Environment and Heritage
RCM	Regional Climate Model
RH	relative humidity
SET	South East and Tablelands
SRES	Special Report on Emissions Scenarios
UNSW	The University of New South Wales
WRF	Weather Research and Forecasting

Summary of findings

Projected changes in snowmaking conditions in the NSW and ACT Alpine region

1. Recent observations and projections indicate that natural snow depth has declined and will continue to decline in the future, meaning that more snow will need to be made artificially to achieve the required snow depth to sustain the ski industry. However, projections indicate that the number of hours suitable for snowmaking will decline substantially over the NSW and ACT Alpine region.
2. Larger absolute decreases in snowmaking conditions are projected for higher elevation areas while larger relative decreases occur at lower elevations. Lower elevation locations might not be suitable for making snow in the future. Specifically, a more than 20% reduction of suitable snowmaking conditions is projected for 2020 to 2039 relative to 1990 to 2009. A up to 60% decrease is projected for 2060 to 2079 relative to 1990 to 2009.
3. If snow is made at warmer temperatures, opportunities for snowmaking may be able to be maintained at current levels (–2°C wet bulb temperature) until 2020 to 2039 (–1°C wet bulb temperature), or until 2060 to 2079 if snow can be made at a 0.5°C wet bulb temperature. However, making snow at warmer temperatures may be associated with trade-offs in cost and quality of snow.
4. The relative changes in future snowmaking conditions are projected to decrease similarly when using different wet bulb temperature thresholds. Regardless of the threshold used, approximately 20% and 50% reductions are projected for the near and far future periods, respectively.

1. Introduction

1.1 Background

The New South Wales (NSW) and Australian Capital Territory (ACT) Alpine region is located in the south-eastern corner of mainland Australia and is the highest mountain range in Australia. Though it comprises only about 0.16% of Australia in size, it is an important region for ecosystems, biodiversity, energy generation and winter tourism. It forms the southern end of the Great Dividing Range, covering a total area of 1.64 million hectares that extend over 500 kilometres. The highest peak, Mount Kosciuszko, rises to an altitude of 2228 metres.

This report is part of a larger project delivered by the NSW Department of Planning, Industry and Environment (DPIE) on the various impacts from climate change on the NSW and ACT Alpine region, hereafter referred to as the Alpine region. The full study region covers the Murray-Murrumbidgee region (MM), South East and Tablelands (SET) and the ACT, bordering the Victorian border in the south (Figure 1).

Australia's most popular snow holiday destination and some of the largest ski resorts in the southern hemisphere are in the Alpine region. The existence of the alpine resorts provides significant benefits to regional areas adjoining them. Many of the alpine shires have high levels of structural unemployment so the alpine industry is important in improving employment outcomes for residents of these regions (NIEIR 2006). In addition, The Snowy Hydroelectric Scheme collects and diverts water from rainfall and snowmelt into the MM rivers, providing irrigation resources for the Murray–Darling Basin, the largest agricultural region in Australia.

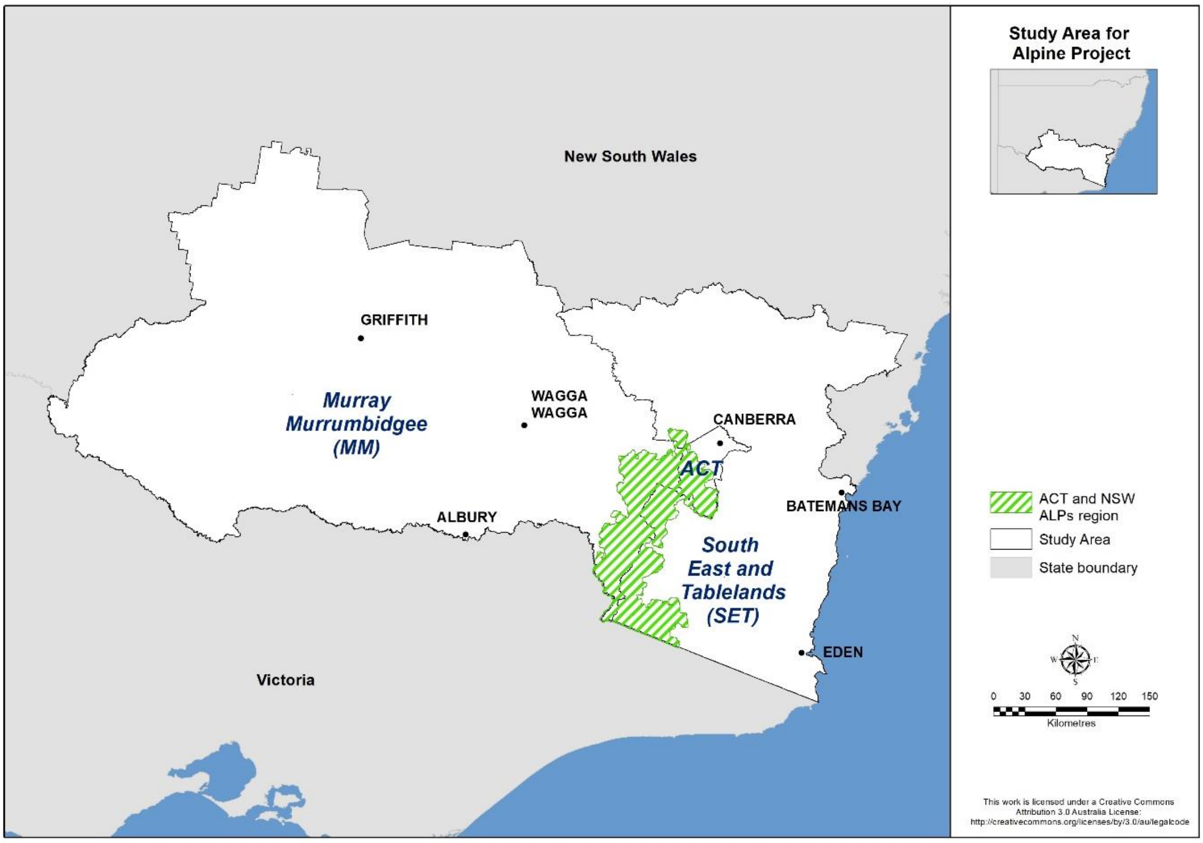

Figure 1 **The study area for the Alpine project, including the NSW and ACT Alpine region, Murray-Murrumbidgee region and South East and Tablelands**

Seasonal snow cover in the Alpine region is critical to some species and winter sports. Several studies have examined long-term snow depth observations from a limited number of sites in the Australia Alpine Region (Ruddell et al. 1990; Nicholls 2005; Hennessy et al. 2008; Davis 2013; Fiddes et al. 2015). These observations begin in the 1950s and 1960s and generally show some consistent decreases in snow depth, although usually statistically insignificant (Figure 2).

A more recent report focusing on Victoria alone demonstrated that since about 1985, maximum snow depths have declined and the snow season has finished earlier as temperatures have increased across Australia (Bhend et al. 2012). Studies have investigated the future climate impact on snow in the Alpine region (Whetton et al. 1996; Hennessy et al. 2008; Fiddes et al. 2015). These studies all use future projections simulated by Global Climate Models (GCMs) to estimate climate change for the Alpine region, despite the GCM resolution being too coarse to capture mountains. These studies project large decreases in snow cover into the future, which will have significant impacts on alpine ecosystems (Pickering 2007; Slatyer 2010). Estimates of future climate change from both GCMs and a statistical downscaling method over Victoria found that statistical downscaling often predicts a larger decline in precipitation than the GCMs (Timbal et al. 2016). This suggests that the use of GCMs to estimate future change may not be appropriate for the Alpine region.

Recently, Di Luca et al. (2018) used 10 kilometre resolution simulations from the NSW/ACT Regional Climate Modelling (NARCliM) project (Evans et al. 2014) to evaluate simulated snow cover and snow depth and undertake future climate projections. Their results show that snow cover extent and snow depths decrease by approximately 15–60% for 2020 to 2039 and 2060 to 2079, relative to 1990 to 2009 (Figure 3). The large decrease in snow cover extent and snow depths will substantially impact the winter ski business.

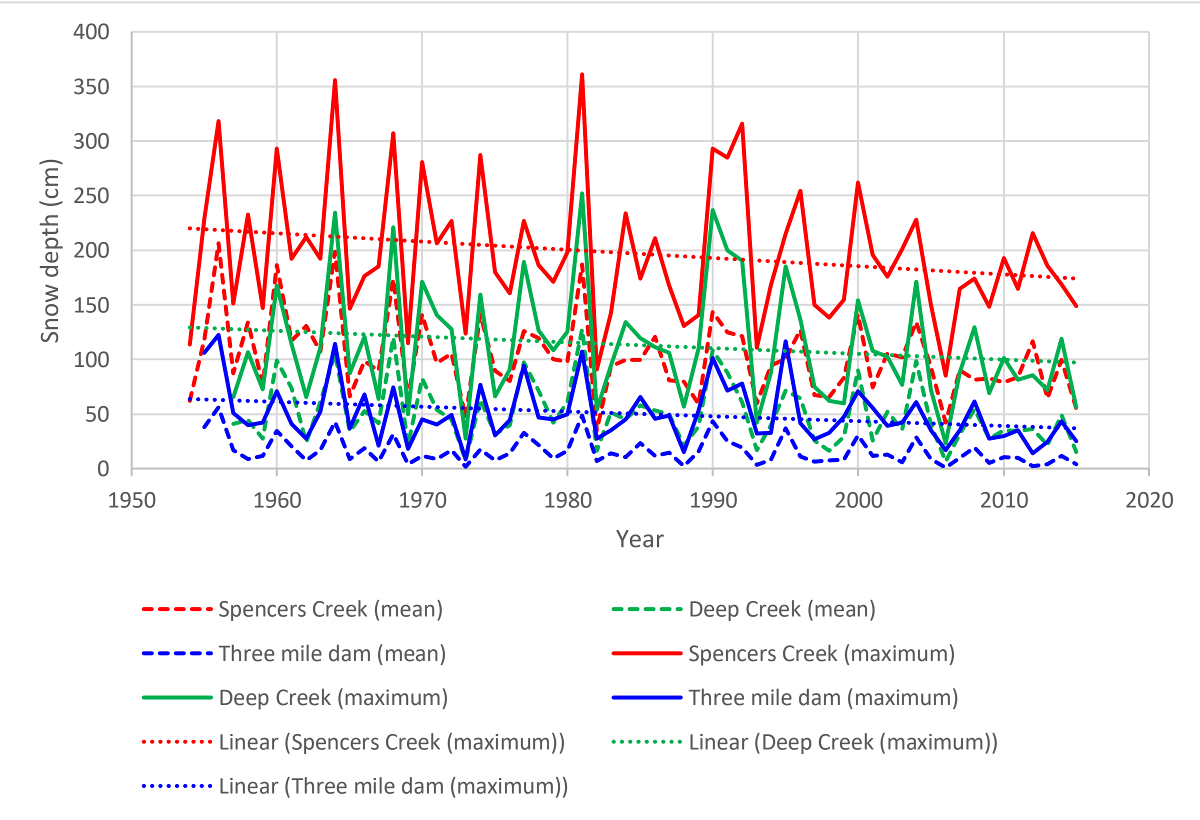

Figure 2 **Observed mean and maximum snow depth (cm) for three snow monitoring sites within NSW, where the solid line = maximum snow depth, dash lines = mean snow depth, dotted line = linear trends in maximum snow depth**

Regional climate modelling outputs project changes to occur in variables important for snowmaking (e.g. temperature, precipitation and snow cover) at six Victorian alpine resorts by the end of century (2070 to 2099) compared to a baseline period of1961 to 2010 (Harris et al. 2016).

Snowmaking was first conducted in Australia as a demonstration exercise at Perisher in 1967, with systematic snowmaking being introduced to Australian ski resort slopes a couple of years later. Most Australian resorts installed significant snowmaking systems during the 1980s and 1990s. Snowmaking is now a common practice and is increasingly used within Australian ski resorts to:

- ensure seasonal length and viability
- improve and maintain the quality of the slopes during the season by topping up natural snow in areas that have poor cover, either because of intensive use by skiers and snowboarders or because of inadequate natural snowpack
- overcome restrictions on skier and snowboarder circulation caused by inadequate levels of natural snow.

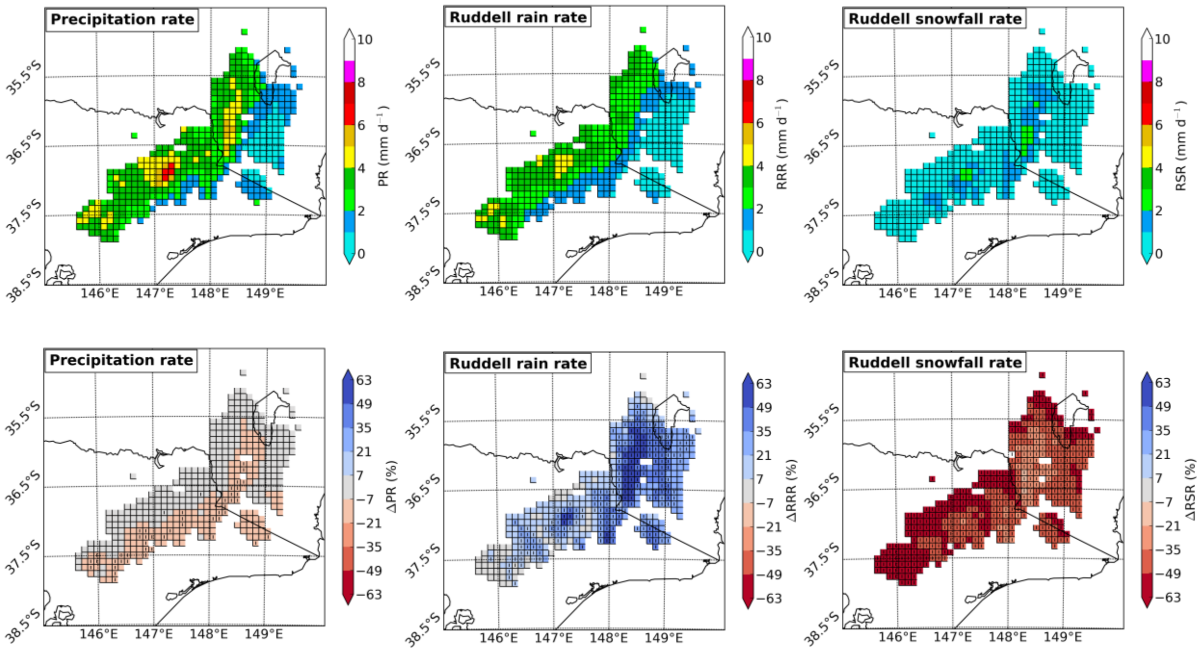

Figure 3 **Simulated precipitation, rainfall and snow for 1990 to 2009 (top row) and their future changes for 2060 to 2079 relative to the 1990 to 2009 baseline period (bottom row) (from Di Luca et al. 2016)**

The proposed snowmaking coverage for the resorts has been determined primarily by identifying the best opportunities for skiing that could be supplied with man-made snow early in the season, and linking these with suitable trails for skier and snowboarder circulation. Environmental conditions are generally also an important consideration influencing the preferred skiing areas, the staging of their development and the location of snowmaking mains. Water supply and maintaining environmental flows in resort creeks is a major planning consideration.

With increases in temperature projected for the future, snowmaking is becoming an increasingly important function at Australian ski resorts to meet the requirements of winter ski sports. Weather conditions are undoubtedly critical to make snow even if snow can currently be made at any temperature. Traditionally, wet bulb temperatures below –2°C were considered suitable for snowmaking. In this study, we use 10 kilometre resolution NARCliM simulations to assess how suitable snowmaking conditions in the Alpine region will change under future climate.

1.2 Objectives

Observations have shown a clear increase in maximum and minimum temperatures and a decrease in precipitation and snow depth for the Alpine region (Di Luca et al. 2016, 2018). Available future snow projections also demonstrate decreases in snow cover, snow depth and snow season length in the future (Di Luca et al. 2016, 2018). To adapt to snow depth declines, snowmaking is playing an increasing role to sustain the ski industry.

The viability of conventional snowmaking is determined by the frequency at which wet bulb temperatures are below some specific thresholds suitable for making snow. In this study, we used outputs of 12 baseline and future Regional Climate Model (RCM) simulations (each with three time periods: 1990 to 2009, 2020 to 2039, and 2060 to 2079) from the NARCliM project to investigate changes in frequency of suitable snowmaking conditions for the Alpine region. The number of hours suitable for snowmaking (based on threshold temperatures, such as –2°C) was calculated for a baseline period (1990 to 2009) and two future periods (2020 to 2039 and 2060 to 2079) for each of the 12 simulations. These time periods were compared to investigate if the frequency of suitable snowmaking will change in the future.

1.3 Outputs

Output	Details	Key users
Report	Projected changes in snowmaking conditions	Researchers
Data (surface layer)	Daily wet bulb temperature for all three epochs Suitable snowmaking conditions for three wet bulb temperature thresholds (–2, –1 and 0.5°C) (60 years) Seasonal and annual suitable snowmaking hours and relative change (%) in the near future and far future	NSW National Parks & Wildlife Service
Maps	Map layouts of the above data (NetCDF)	Councils, ski resorts, etc.

2. Methods

2.1 Source of data

NARCliM simulations from four CMIP3 GCMs were used to drive three RCMs to form a 12-member GCM/RCM ensemble (Evans et al. 2014). The four selected GCMs are MIROC3.2, ECHAM5, CCCMA3.1, and CSIRO-MK3.0 (hereafter referred to in short-hand as MIROC, ECHAM, CCCMA and CSIRO). For the future projections the Special Report on Emissions Scenarios (SRES) business-as-usual A2 scenario was used (IPCC 2000). The three selected RCMs are three physics scheme combinations of the Weather Research and Forecasting (WRF) model. Each simulation consists of three 20-year runs (1990 to 2009, 2020 to 2039 and 2060 to 2079). The four GCMs were chosen based on a number of criteria: i) adequate performance when simulating historic climate; ii) most independent; iii) cover the largest range of plausible future precipitation and temperature changes for Australia. The three RCMs correspond to three different physics scheme combinations of the WRF V3.3 model (Skamarock et al. 2008), which were also chosen for adequate skill and error independence, following a comprehensive analysis of 36 different combinations of physics parameterisations over eight significant East Coast Lows (ECLs) (Evans et al. 2012; Ji et al. 2014). For the selected three RCMs, the WRF Double Moment 5-class (WDM5) microphysics scheme and NOAH land surface scheme are used in all cases. Refer to Evans et al. (2014) for more details on each physics scheme.

We acknowledge that the results are model dependent (as all model studies are) but through the use of this carefully selected ensemble we have attempted to minimize this dependence. By using this model selection process, we have shown that it is possible to create relatively small ensembles that are able to reproduce the ensemble mean and variance from the large parent ensemble (i.e. the many GCMs) as well as minimize the overall error (Evans et al., 2013a).

Some initial evaluation of NARCliM simulations shows that they have strong skill in simulating the precipitation and temperature of Australia, with a small cold bias and overestimation of precipitation on the Great Dividing Range (Evans et al. 2013b, Ji et al. 2016). The differing responses of the different RCMs confirm the utility of considering model independence when choosing the RCMs. The RCM response to large-scale modes of variability also agrees well with observations (Fita et al. 2016). Through these evaluations we found that while there is a spread in model predictions, all models perform adequately with no single model performing the best for all variables and metrics. The use of the full ensemble provides a measure of robustness such that any result that is common through all models in the ensemble is considered to have higher confidence.

For ease of reference in this report, the simulations driven by the same GCM were referred to as ‘same GCM driven simulations’. The simulations using the same RCM were referred to as ‘same RCM used simulations’. In total, there were four same GCM driven simulations (average of three members) and three same RCM used simulations (average of four members). The outputs from NARCliM are used to calculate the wet bulb temperature.

2.2 Analysis

For each grid point within the NARCliM domain, 3-hourly wet bulb temperature was calculated using simulated temperature, pressure and relative humidity for 12 simulations, each across three time periods (1990 to 2009, 2020 to 2039 and 2060 to 2079).

Wet bulb temperatures below –2°C were considered suitable for snowmaking, as this corresponds to peak efficiency in snowmaking (snow can be made at much warmer temperatures at increasing cost). The total number of hours for suitable snowmaking is then accumulated for each month and each year and used to analyse long-term mean monthly distribution and the inter-annual variability.

The changes in the number of hours suitable for snowmaking, hereafter suitable snowmaking hours, are expressed as differences and relative changes between the future periods (2020 to 2039 and 2060 to 2079) and the baseline period (1990 to 2009). The results for each ensemble member were averaged to get the ensemble mean.

There are four ski resorts within New South Wales, with different elevations. We analyse differences in snowmaking conditions for each of them. The four sites are located at relatively high elevations throughout the Alpine region (Table 1).

The critical temperature for traditional snowmaking is a wet bulb temperature of approximately –2°C, but recent advances in snowmaking approaches enable snow to be made at higher temperatures. 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.

Table 1 Location and elevation for four ski resorts in the NSW and ACT Alpine region

Sites	Latitude	Longitude	Elevation (m)
Charlotte Pass	–36.423	148.329	1,832
Perisher	–36.404	148.414	1,881
Selwyn	–35.908	148.452	1,855
Thredbo	–36.500	148.300	1,780

Wet bulb temperature

The wet bulb temperature is the temperature that a parcel of air would have if it were cooled to saturation (100% relative humidity) by the evaporation of water into it, with the latent heat being supplied by the parcel. The wet bulb temperature is the lowest temperature that can be reached under current ambient conditions by the evaporation of water only. Wet bulb temperature is largely determined by both actual air temperature (dry-bulb temperature) and the amount of moisture in the air (humidity). At 100% relative humidity, the wet bulb temperature equals the dry-bulb temperature.

Wet bulb temperature incorporates relative humidity, which determines the temperature at which snow can be made. The calculation of wet bulb temperature, 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 climate model outputs.

Wet bulb temperature calculations

Wet bulb temperature was calculated using model output for 2-metre air temperature, relative humidity (RH) and atmospheric pressure, using the standard equations used by the National Oceanographic and Atmospheric Administration:

1. Saturation vapour pressure (es):

   $es = 6.112 \ast 10^{((7.5 \ast T) / (T + 237.3))}$, where T = dry bulb temperature (°C)

2. Actual vapour pressure, hPa (e):

   $e = (es \ast RH) / 100$

3. Initial conditions for the iteration:

   Saturation vapour pressure at each increment:

   $Ewg = 6.112 \ast 10^{((7.5 \ast Tw)/(Tw + 237.3))}$

   Actual vapour pressure at each increment:

   $eg = Ewg - ((P \ast (T - Tw)) \ast 0.00066 \ast (1 + (0.00115 \ast Tw)))$

   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°, and the increment being divided by 10 when the consecutive vapour pressure difference (Ed) changed sign. The iteration was stopped when the vapour pressure difference was equal to zero or the absolute value of Ed was less than 0.005.

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

2.3 Quality control

The input data used in the study (temperature, relative humidity and surface pressure) have been quality controlled and released for public use. The analysis method is similar to what was used in the study for Victoria's ski resorts (Harris et al. 2016), which was externally reviewed by experts at the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

The method has been reviewed by Dr Tom Remenyi at ACE CRC's Climate Futures who was working on the Victoria project (Harris et at. 2016). The report was reviewed both internally and externally, and followed the procedures as set out in DPIE's Scientific Rigour Position Statement (OEH 2013).

2.4 Data storage and access

All output data were converted to raster format (ArcGIS ESRI grid) and supplied to the MCAS-S (Multi-Criteria Analysis Shell for Spatial Decision Support) datapacks for distribution and storage. All input data to the model and by-products are stored on hard disk drives. All data are in the NARCliM coordinate system. The extent of the datasets includes the MM region, ACT and SET with the boundary at top: –32.671254, left: 143.317445, right: 150.745676, and bottom: –37.505077.

3. Results

In this section, we will first present suitable snowmaking hours over the Alpine region using wet bulb temperature below a –2°C threshold, then show how snowmaking changes in the future, including seasonal variation. This will be followed by an analysis of the four individual NSW ski resorts. We then proceed to test wet bulb temperature thresholds below –1°C and 0.5°C to compare with the snowmaking results presented for the –2°C threshold.

3.1 Snowmaking below –2°C

Annual mean suitable snowmaking time

Annual mean suitable snowmaking hours for the baseline and two future periods are calculated for each of the 12 ensemble members. The ensemble mean is presented in Figure 4.

In the baseline projections (Figure 4), there are more than 600 suitable snowmaking hours a year for high elevation areas (above 1700 m) and fewer than 100 suitable snowmaking hours a year for lower elevation areas (below 1500 m). The gradient of suitable snowmaking condition within the Alpine region is quite large, indicating that snowmaking condition is sensitive to elevation. There are essentially zero snowmaking hours below 500 metres.

Large decreases in suitable snowmaking hours are projected for 2020 to 2039 and 2060 to 2079 relative to 1990 to 2009 (Figure 4). Lower elevation sites are projected to become unsuitable for making snow, and higher elevation sites are projected to have about 300 fewer suitable snowmaking hours for 2060 to 2079. The largest relative changes are projected for lower elevation areas, with up to 80% fewer suitable snowmaking hours in the far future (figure not shown).

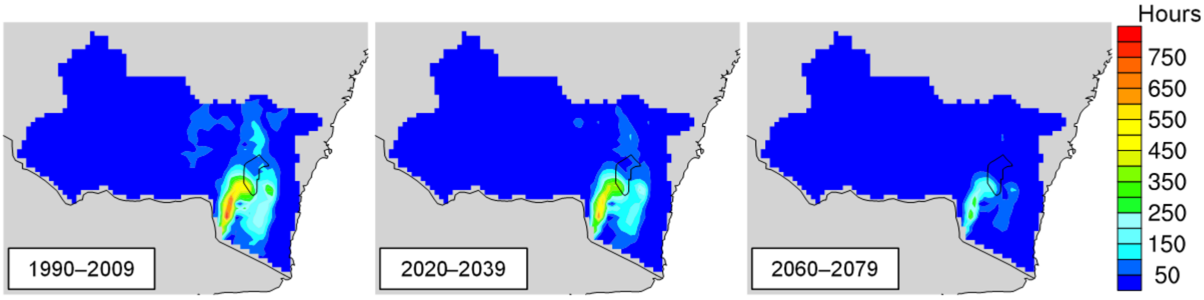

Figure 4 **Suitable snowmaking conditions (in hours) for 1990 to 2009, 2020 to 2039 and 2060 to 2079 for the –2°C threshold**

Monthly variation in time suitable for snowmaking

Accumulated monthly suitable snowmaking hours is presented in Figure 5. The three solid lines are averages of the 12 NARCliM ensemble members for the baseline and future periods. The three dashed lines show the best-case scenario (largest value in the 12-member ensemble), and dotted lines show the worst-case scenario (smallest value in the 12-member ensemble).

Across the Alpine region, compared to the baseline period, there is a clear decrease in the absolute number of suitable snowmaking hours into the future. The seasonal distribution is relatively unchanged, with the peak occurring in winter (June, July, August – JJA); however, there is a significant contraction of the entire season, with much fewer suitable snowmaking hours in the shoulder seasons (April, May and September, October). The largest absolute decreases are projected to occur in winter.

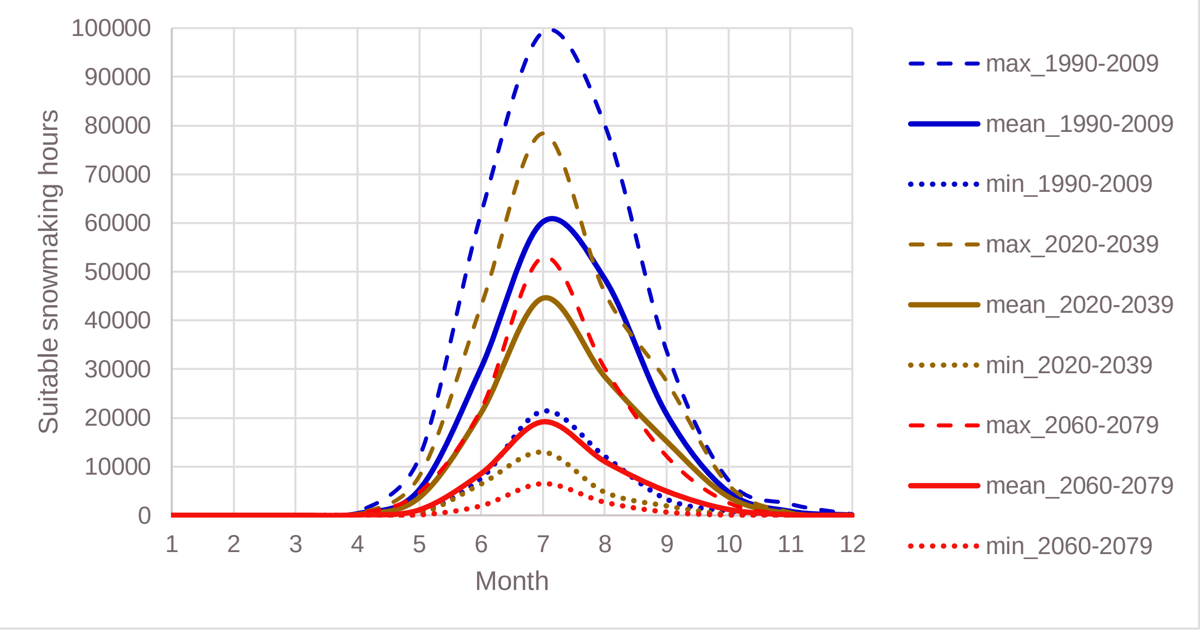

Figure 5 **Simulated monthly distribution of suitable snowmaking conditions for the Alpine region for best (dashed lines), mean (solid lines) and worst-case (dotted lines) scenarios in the 12-member NARCliM ensemble for the –2°C threshold**

The differences between the best-case and worst-case scenarios are very large (up to 400% for the best-case scenario relative to the worst-case scenario in July), especially for the winter season. This implies there is large uncertainty within the ensemble. This is understandable as GCMs selected in the NARCliM project were chosen based on a number of criteria that include spanning the range of future changes in the GCM ensemble (Evans et al. 2014).

Differences between GCM/RCM simulations

Changes in suitable snowmaking hours for 2060 to 2079 relative to 1990 to 2009 are large for the Alpine region. Differences in projections across GCM simulations are large, although they all project larger decreases in lower elevation areas than in higher elevation areas (Figure 6). Simulations based on the CCCMA model project the largest decreases in suitable snowmaking hours for lower elevation (> 90%) and higher elevation areas (> 70%). Simulations driven by MIROC project similar decreases for lower elevation areas, but smaller decreases for higher elevation areas (60–70%). Both the ECHAM and CSIRO driven simulations project less severe changes, about half those of CCCMA and MIROC.

The three RCM simulations generally project similar decreases in suitable snowmaking hours for the Alpine region with 60–70% decreases for higher elevation areas and 80–90% decreases for lower elevation areas. For areas outside the Alpine region boundary, there are some differences between the three RCM simulations since the R3 simulations projected slightly larger increases in temperature.

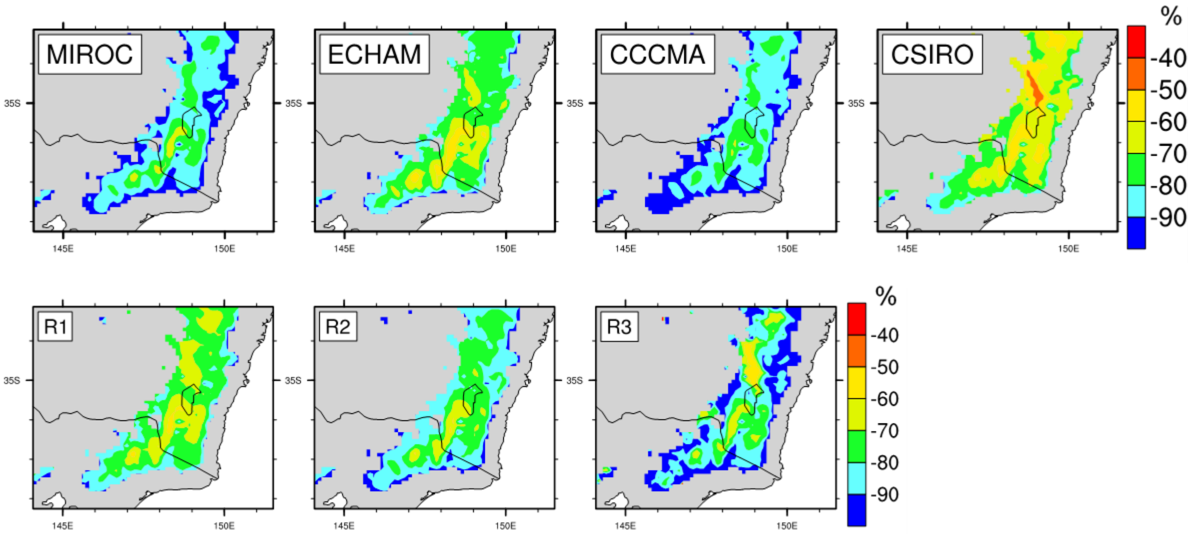

Figure 6 **Relative changes in snowmaking conditions (%) for 2060 to 2079 relative to the 1990 to 2009 baseline period for four GCM and three RCM simulations for the –2°C threshold**

Inter-annual variability for ski resorts

Suitable snowmaking hours have clear inter-annual variability (Figure 7), which is related to the inter-annual variation in temperature. Here we show results for four ski resorts. Correlation of suitable snowmaking hours across different sites is related to elevation, with those sites at similar elevations correlating the best (> 0.9). Generally, snowmaking conditions show similar inter-annual variability for these four ski resorts.

Although there is little difference in peak elevation (< 100 m across all four resorts), the differences in suitable snowmaking conditions are large. For example, Thredbo is 101 metres lower than Perisher. The difference in suitable snowmaking conditions is about 150 hours a year, about 25% of the annual suitable snowmaking time of Perisher. This indicates that snowmaking conditions are very sensitive to elevation.

A decreasing trend in snowmaking conditions can be observed for each ski resort for each of the 20-year projection periods. Changes in suitable snowmaking conditions are projected to decrease 20–30% for 2020 to 2039 relative to 1990 to 2009, and 60–70% for 2060 to 2079 relative to 1990 to 2009, for all ski resorts.

Monthly variation for ski resorts

Within the model, July is the best time for making snow in all locations. Suitable snowmaking hours across the year are longer for higher elevation locations, which start earlier and finish later. The opposite is true for lower elevation locations, where shorter snowmaking hours are projected across the year that start later and finish earlier.

Larger decreases in suitable snowmaking hours are projected for all locations, especially in the peak month, July, for higher elevation locations (Figure 8). Under a future climate, the period of suitable snowmaking hours will get shorter (that is, start later and finish earlier) at all locations. Differences in suitable snowmaking conditions between different ski resorts are larger in JJA than the shoulder seasons, with the largest difference in July.

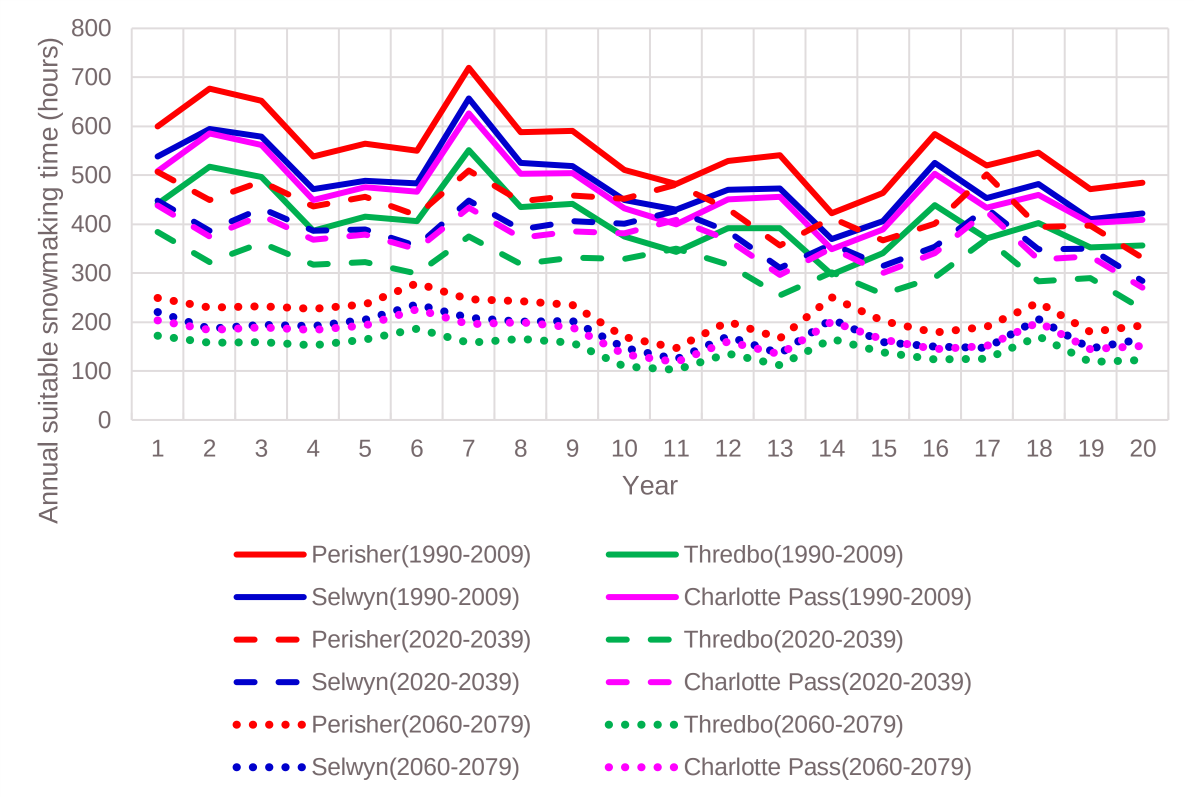

Figure 7 **Inter-annual variability of suitable snowmaking time for four ski resorts for 1990 to 2009, 2020 to 2039 and 2060 to 2079 for the –2°C threshold**

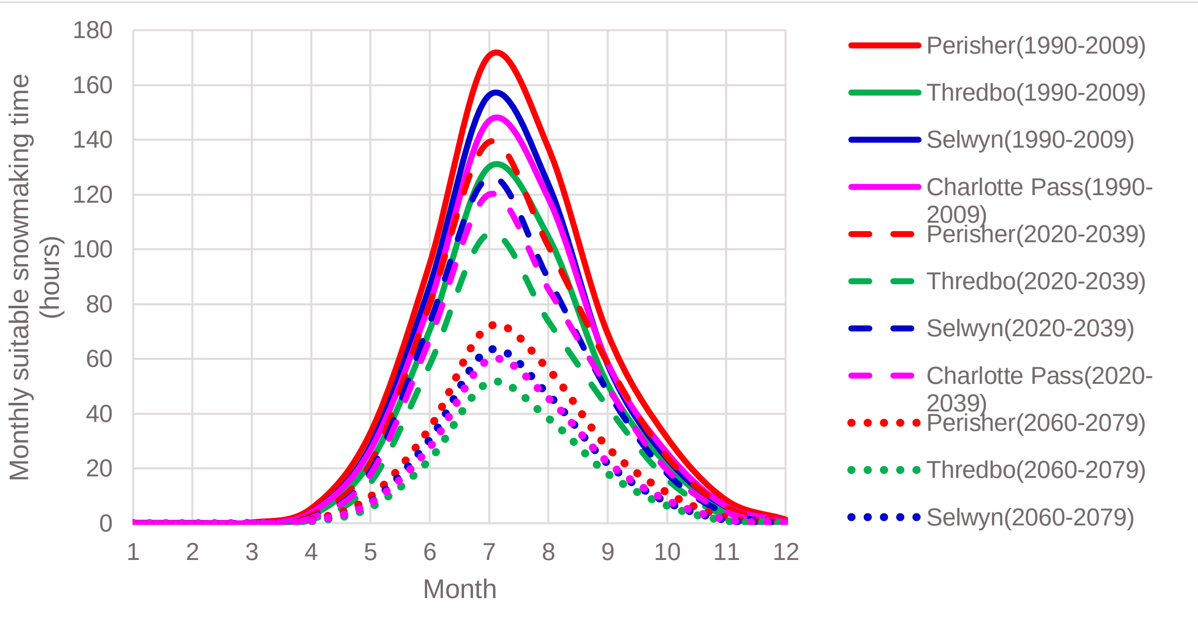

Figure 8 **Monthly suitable snowmaking time for four ski resorts for 1990 to 2009, 2020 to 2039 and 2060 to 2079 for the –2°C threshold**

Relative changes in annual suitable snowmaking conditions

Changes in annual suitable snowmaking hours for 2020 to 2039 relative to 1990 to 2009 are relatively small (Figure 9). The major decreases are observed in the Alpine region and along high elevation areas within SET, where decreases of more than 20% are projected. Relatively smaller decreases, however, are projected for the mountain peaks in the Alpine region. Small decreases are projected for elsewhere. This indicates that future climate change mostly impacts on snowmaking conditions for high topography areas.

Future changes in snowmaking conditions are much larger for the far future compared to the near future (Figure 9 & Figure 10). A greater than 50% decrease in annual suitable snowmaking hours is projected for the Alpine region in the far future, with much smaller decreases elsewhere (Figure 10).

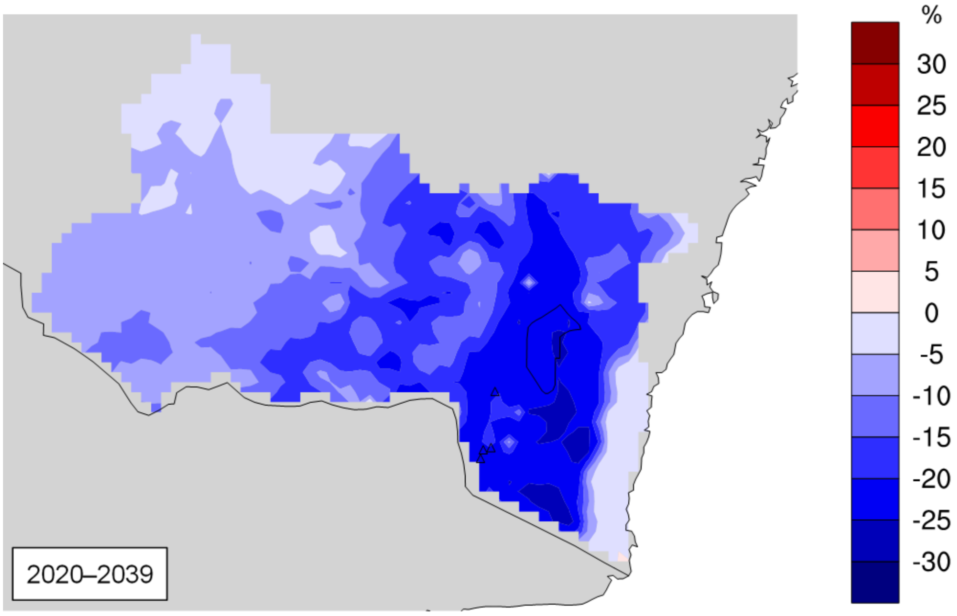

Figure 9 **Changes in suitable snowmaking conditions (%) for 2020 to 2039 relative to the 1990 to 2009 baseline period for the –2°C threshold**

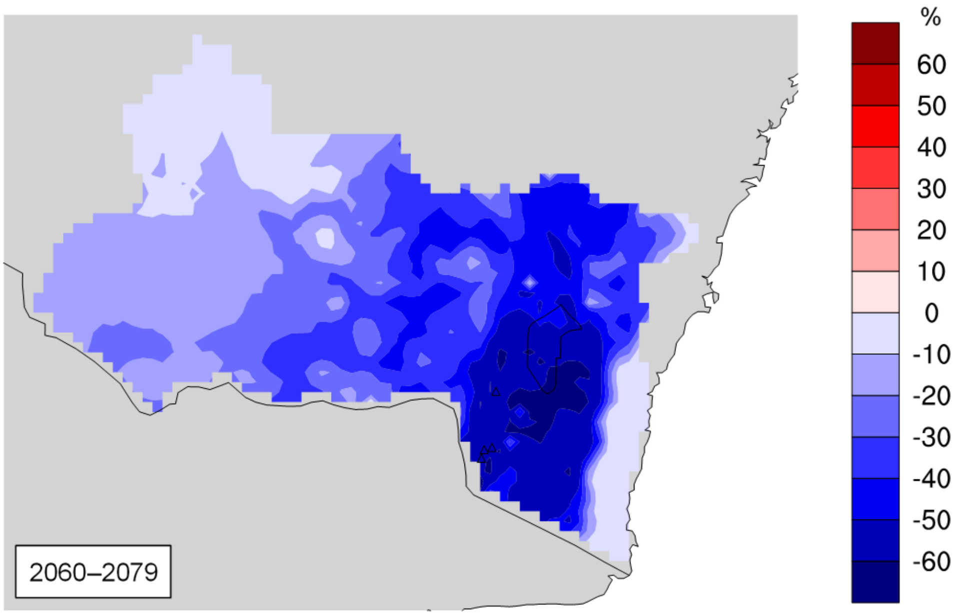

Figure 10 **Changes in suitable snowmaking conditions (%) for 2060 to 2079 relative to the 1990 to 2009 baseline period for the –2°C threshold**

3.2 Snowmaking below –1°C

Annual mean suitable snowmaking time

The annual mean suitable snowmaking hours for the baseline and two future periods are presented in Figure 11. When compared with Figure 4, there is about 50% more suitable snowmaking time for the Alpine region and high elevation areas in the SET region. When snow can be made at a higher wet bulb temperature (–1°C threshold), the lower elevation areas surrounding the Alpine region have 100–200 hours a year suitable for making snow for 1990 to 2009.

A 200–300 hour a year decrease in suitable snowmaking conditions is projected for the Alpine region for 2020 to 2039 relative to 1990 to 2009. The greatest decrease is observed at the highest elevations. There are 600–800 hours a year still suitable for making snow for 2020 to 2039, which is at a similar range of suitable snowmaking conditions for 1990 to 2009 using –2°C as threshold.

Similar to Figure 4, changes for 2060 to 2079 for the –1.5°C threshold are much larger than those for 2020 to 2039 (Figure 11). The greatest decreases are observed at the highest elevations. At the lower elevations, there is almost no time suitable for snowmaking.

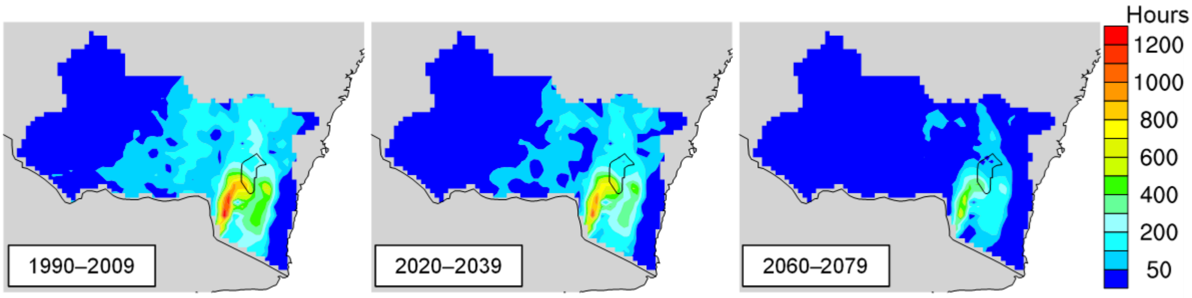

Figure 11 Suitable snowmaking conditions (in hours) for 1990 to 2009, 2020 to 2039 and 2060 to 2079 for the –1°C threshold

Inter-annual variability for ski resorts

Suitable snowmaking hours for a –1°C threshold have similar inter-annual variability to those using –2°C as a threshold (shown in Figure 7); however, the magnitude of variability is larger (Figure 12). A decreasing trend is found for each ski resort for both future projection periods. Differences between 2020 to 2039 and 1990 to 2009 are relatively small for each ski resort (approximately 20%); however, those for 2060 to 2079 relative to 1990 to 2009 are between 50 and 60%.

Monthly variations for ski resorts

Monthly variations in suitable snowmaking hours using a –1°C threshold (Figure 13) are similar to those using a –2°C threshold (Figure 8), for each ski resort and each time period, but many more suitable snowmaking hours are available when using a –1°C threshold. Most of the additional available snowmaking hours are found in JJA, and the remainder in the shoulder seasons.

The absolute changes in suitable snowmaking hours for future periods relative to the historical period are also large when using a –1°C threshold; however, the relative changes in suitable snowmaking hours are similar (or even a little smaller). Again, relative changes in suitable snowmaking hours are small for 2020 to 2039 (about 20%) and large for 2060 to 2079 (50%), relative to 1990 to 2009.

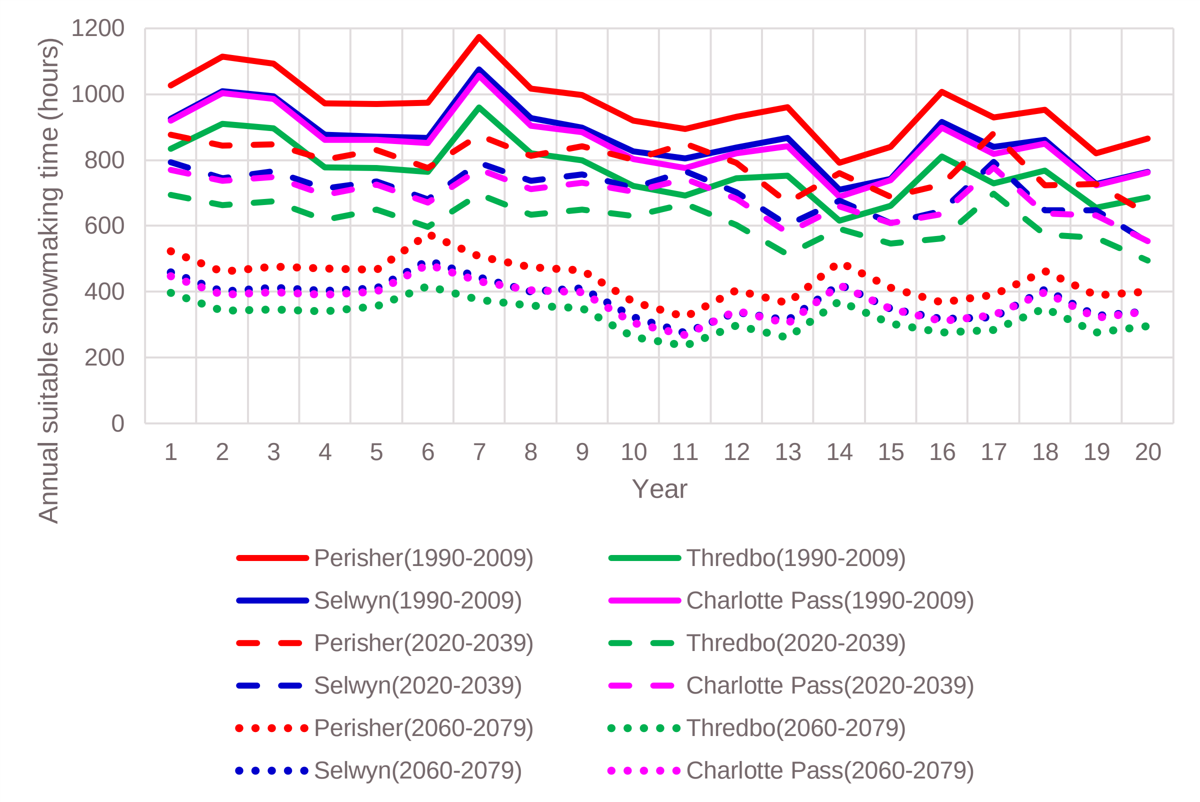

Figure 12 **Inter-annual variability of suitable snowmaking time for four ski resorts for 1990 to 2009, 2020 to 2039 and 2060 to 2079 for the –1°C threshold**

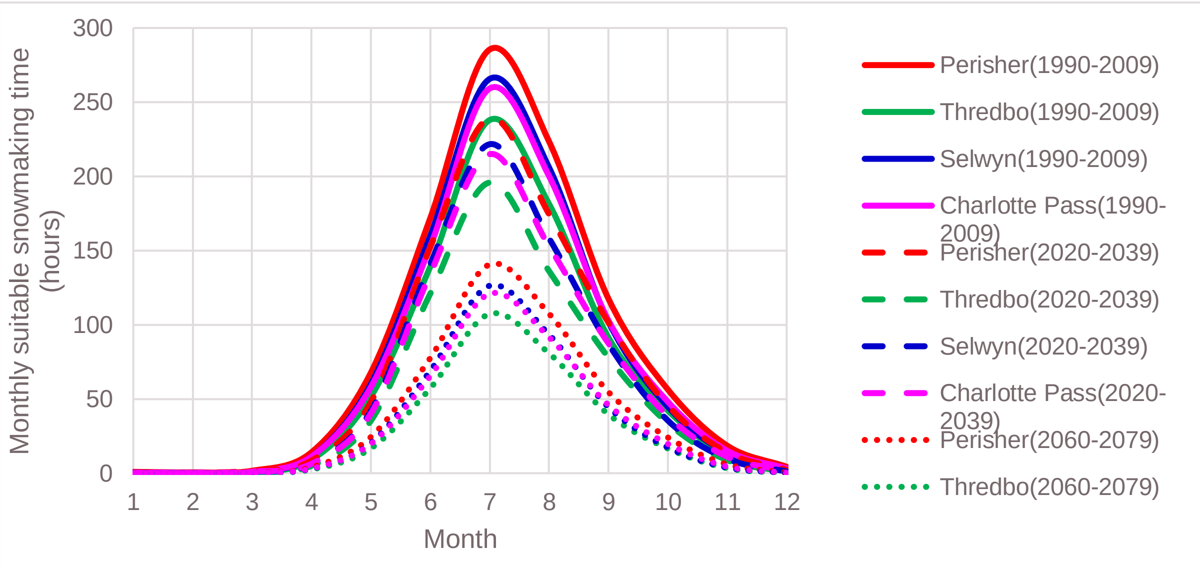

Figure 13 **Monthly suitable snowmaking time for four ski resorts for 1990 to 2009, 2020 to 2039 and 2060 to 2079 for the –1°C threshold**

Relative changes in annual suitable snowmaking conditions

The changes for 2020 to 2039 relative to 1990 to 2009 (Figure 14) span a similar range to those shown in Figure 9. The large decreases are observed in the Alpine region and along high topography areas within SET, where 20–25% decreases are projected; however a smaller decrease (15–20%) is found for the mountain peaks in the Alpine region. A small decrease is projected for other regions. This indicates that future climate change mostly impacts on snowmaking conditions for high topography areas.

Future changes in snowmaking conditions are much larger for the far future projections than the near future projections (Figure 15). A more than 50% decrease in snowmaking conditions is projected for the Alpine region and much smaller elsewhere, which is similar to what is shown in Figure 10.

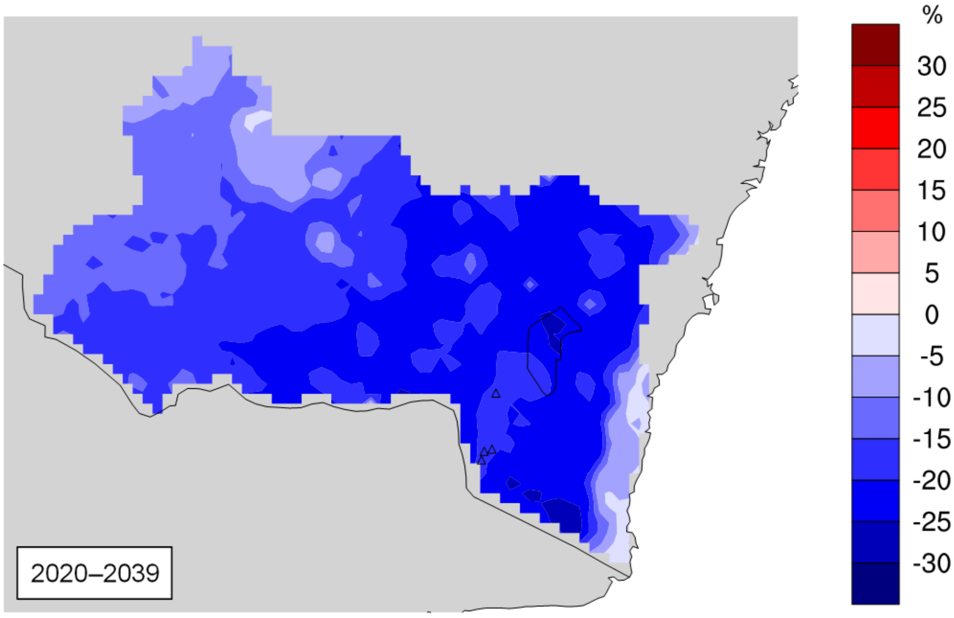

Figure 14 Changes in suitable snowmaking conditions (%) for 2020 to 2039 relative to the 1990 to 2009 baseline period for the –1°C threshold

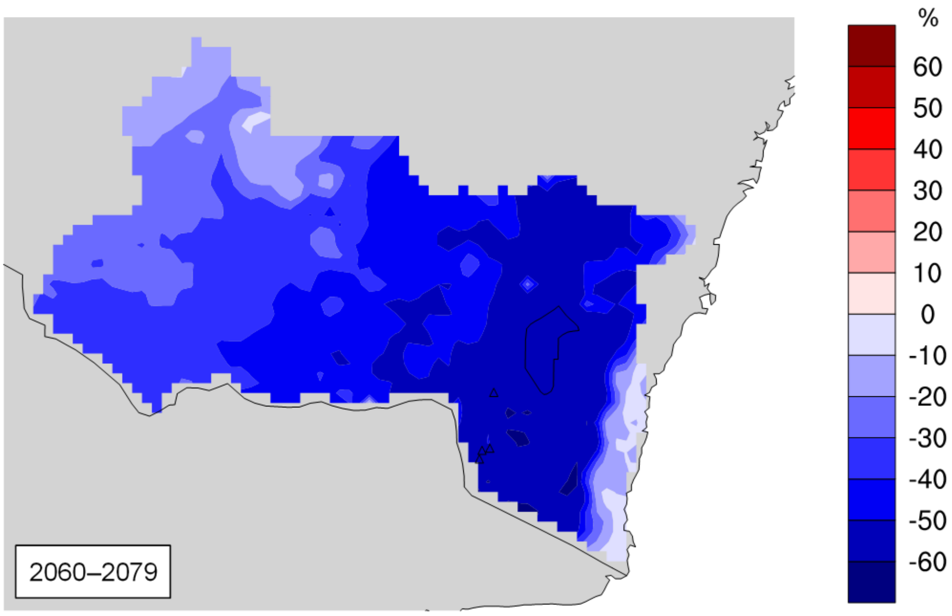

Figure 15 Changes in suitable snowmaking conditions (%) for 2060 to 2079 relative to the 1990 to 2009 baseline period for the –1°C threshold

3.3 Snowmaking below 0.5°C

Annual mean suitable snowmaking time

The annual mean suitable snowmaking hours for the baseline period and two future projection periods are presented in Figure 16. When compared with Figure 4, there is approximately 120% more suitable snowmaking time for the alpine and high elevation areas in the SET region. When snow can be made at an even higher wet bulb temperature (0.5°C), lower elevation areas surrounding the Alpine region have 200–400 hours a year suitable for making snow in the 1990 to 2009 baseline period.

There is a 400–600 hour a year decrease in suitable snowmaking condition projected for the Alpine region for 2020 to 2039 relative to 1990 to 2009. The greatest decrease is at the highest elevations. There are 800–1000 hours a year suitable for making snow for 2060 to 2079. This is within similar range of suitable snowmaking condition for 1990 to 2009 using –2°C as the threshold.

Similar to Figure 4, changes for 2060 to 2079 are much larger than that for 2020 to 2039. The largest decreases are observed at the highest elevations, and there are fewer hours for suitable snowmaking for lower elevation areas.

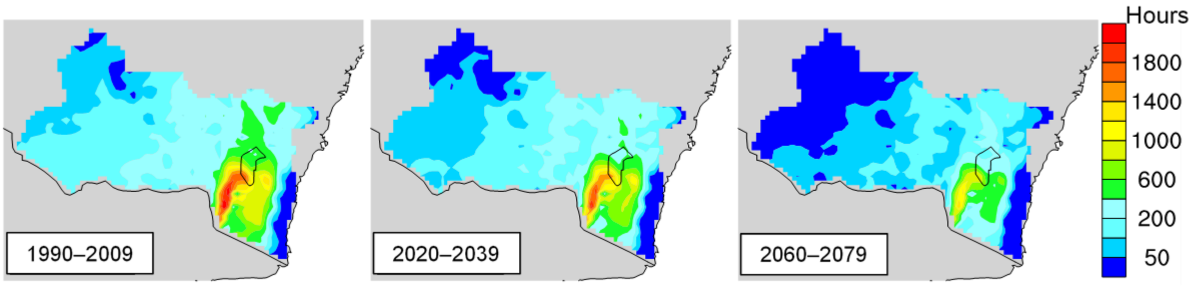

Figure 16 **Suitable snowmaking conditions (in hours) for 1990 to 2009, 2020 to 2039 and 2060 to 2079 for the 0.5°C threshold**

Inter-annual variability for ski resorts

When using a 0.5°C threshold, suitable snowmaking hours have similar inter-annual variability to those using a –2°C threshold (Figure 7); however, the magnitude of variability is much larger (Figure 17). Again, a decreasing trend can be observed for each ski resort for all three time periods. Differences between 2020 to 2039 and 1990 to 2009 are relatively small for each ski resort (~20%); however, those for 2060 to 2079 relative to 1990 to 2009 are about 50%.

Monthly variation for ski resorts

Monthly variations of suitable snowmaking hours when using a 0.5°C threshold (Figure 18) are similar to that for using a –2°C threshold (Figure 8), for each ski resort and each time period; however, much more suitable snowmaking hours are available when using a 0.5°C threshold. Most of the extra available snowmaking hours are between June and August and the rest of the change is in the shoulder seasons.

The actual changes between different time periods are also large when using a 0.5°C threshold; however, the relative change is smaller when compared with using a –2°C and –1°C threshold. Again, the relative change is small for 2020 to 2039 (15–20%), and large for 2060 to 2079 (40–50%).

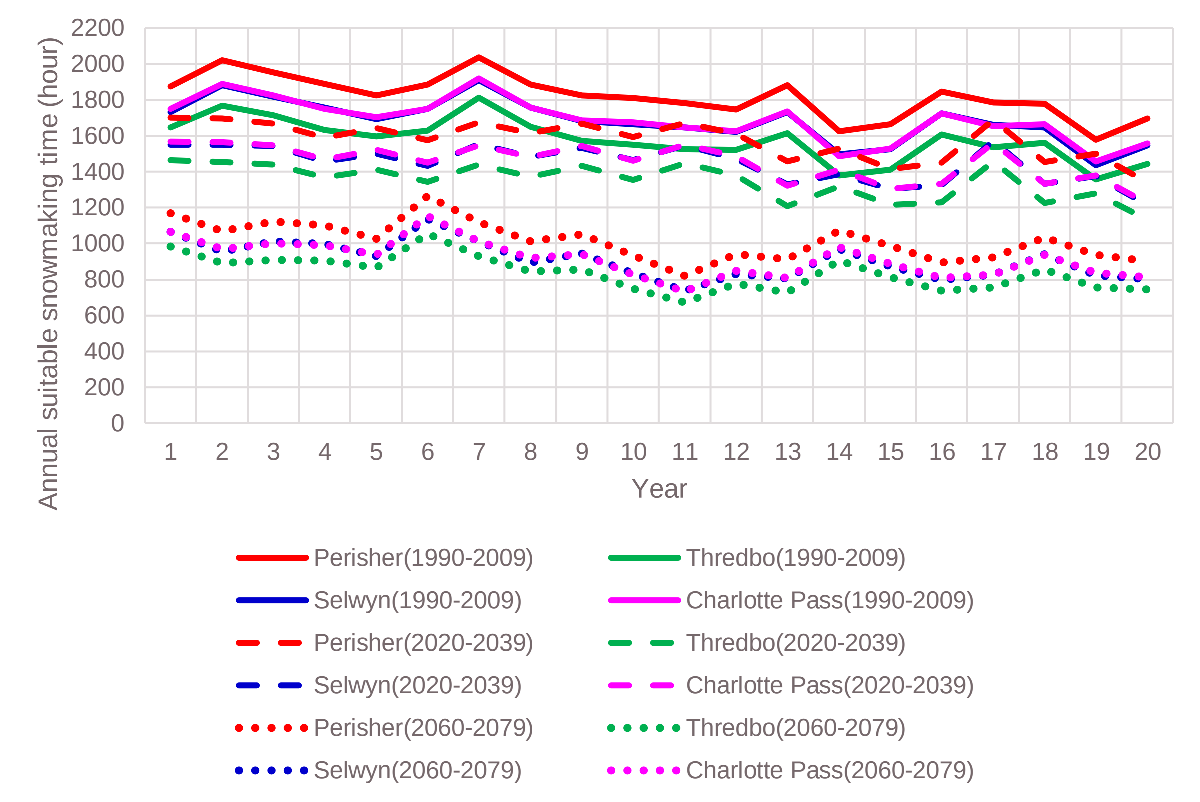

Figure 17 **Inter-annual variability of suitable snowmaking time for four ski resorts for 1990 to 2009, 2020 to 2039 and 2060 to 2079 for the 0.5°C threshold**

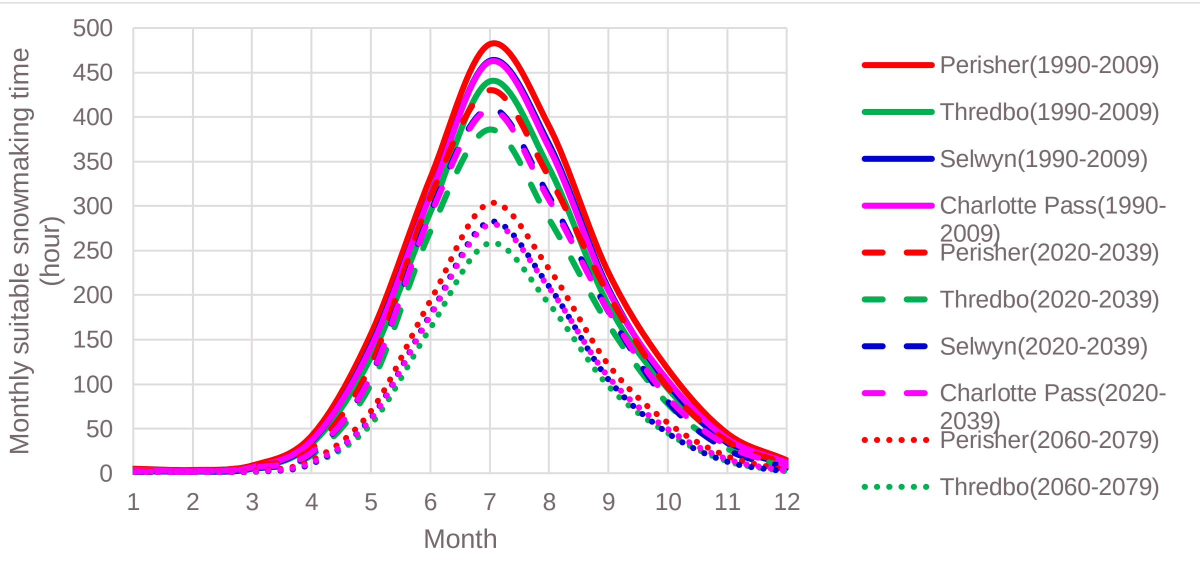

Figure 18 **Monthly suitable snowmaking time for four ski resorts for 1990 to 2009, 2020 to 2039 and 2060 to 2079 for the 0.5°C threshold**

Relative changes in annual suitable snowmaking conditions

The changes for 2020 to 2039 relative to 1990 to 2009 (Figure 19) are at similar ranges to those shown in Figure 9. The major changes are observed in the Alpine region and along high topography areas within SET, where 15–20% decreases are projected; however relatively smaller decrease (10–15%) for the mountain peaks in the Alpine region. Larger decreases (20–25%) are projected elsewhere, which is very different from those using a –2°C and –1°C threshold (see Figure 9 and Figure 14). This indicates that future climate change mostly impacts on snowmaking conditions not only for high topography areas but also for lower elevation areas.

Future changes in snowmaking conditions are much larger for the far future than near future. A 40–50% decrease is projected for the Alpine region, with 50–60% decreases projected in surrounding lower elevation areas and 40–50% for the MM region (Figure 20).

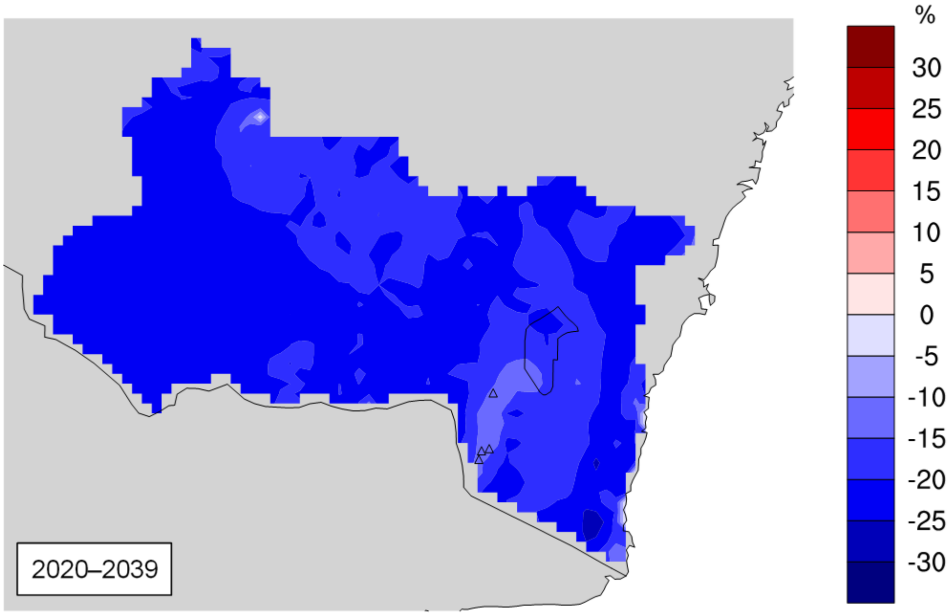

Figure 19 Changes in suitable snowmaking conditions (%) for 2020 to 2039 relative to the 1990 to 2009 baseline period for the 0.5°C threshold

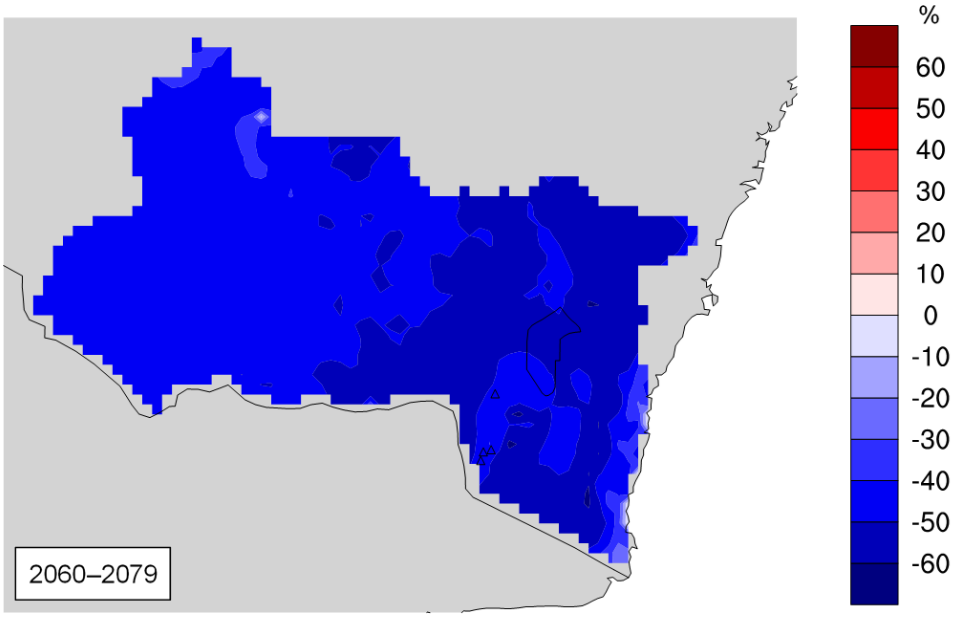

Figure 20 Changes in suitable snowmaking conditions (%) for 2060 to 2079 relative to the 1990 to 2009 baseline period for the 0.5°C threshold

4. Discussion

4.1 Key findings

Suitable snowmaking conditions are sensitive to two key parameters: wet bulb temperature threshold and elevation. When snow can be made in a higher temperature environment (–1°C or 0.5°C), there is far more time suitable for snowmaking (note that cost of snowmaking and snow quality are not considered). The higher elevation ski resort generally has more time suitable for snowmaking. In addition, we find the following:

- There is a clear monthly variation in snowmaking conditions with peak values in July. Inter-annual variations in snowmaking conditions are correlated with mean temperature.
- There is an approximately 20% decrease in snowmaking conditions projected for 2020 to 2039 relative to 1990 to 2009, and a 50–60% decrease for 2060 to 2079 relative to 1990 to 2009.
- Larger absolute decreases in snowmaking conditions are projected for higher elevation areas, but larger relative decreases for lower elevation areas. Lower elevation locations might not be suitable for making snow in the future.
- Regardless of the threshold used, the future changes in suitable snowmaking hours are similar (around 20% and around 50% reduction for near and far futures).

4.2 Limitations and further research

The following factors influence the accuracy of the findings in Section 4.1.

Daily time-step NARCliM GCM/RCM projections (temperature, humidity, etc.) are at a spatial resolution of approximately 10 kilometres. This is considered rather coarse for the Alpine region where elevation might change a few hundred metres between neighbouring cells. As the suitable snowmaking conditions are very sensitive to the elevation, the inter-annual and monthly results are only for the specific locations of the four ski resorts. Some ski resorts might span a few hundred metres in elevation, and higher topography areas generally have more hours suitable for making snow.

In addition, there are large uncertainties between the 12 NARCliM ensemble members (Figure 6). This is understandable as GCMs selected in the NARCliM project were chosen based on criteria that include spanning the range of future changes in the GCM ensemble (Evans et al. 2014). For Australia, MIROC projects a slightly warmer and much wetter future, CCCMA projects an extremely warmer and slightly wetter future, CSIRO slightly warmer and drier, and ECHAM projects an extremely warmer and slightly drier future. The differences in temperature and humidity projected by the four GCMs result in diverse change in magnitude of suitable snowmaking conditions for four ‘same GCM used simulations’ shown in Figure 6. This is consistent with the findings from previous uncertainty studies, which suggest that the largest uncertainty in future projections is sourced from the GCMs (Chen et al. 2011; Vaze et al. 2011; Teng et al. 2012).

5. Conclusion

The NARCliM outputs are used in the study for calculating wet bulb temperature. Three wet bulb temperature thresholds (–2°C, –1°C and 0.5°C) were used to quantify suitable snowmaking hours for 1990 to 2009 (baseline), 2020 to 2039 (near future) and 2060 to 2079 (far future). Results for the multi-model mean, instead of each ensemble member, are presented in this study. The results show that:

- A more than 20% reduction of snowmaking conditions is projected for the near future, and a up to 60% reduction is projected for the far future.
- Larger absolute decreases in snowmaking conditions are projected for higher elevation areas but larger relative decreases are projected for lower elevation areas. In the future, lower elevation areas may not be suitable for snowmaking.
- If snow is made at warmer temperatures, opportunities for snowmaking may be maintained at current levels (–2°C wet bulb temperature) until 2020 to 2039 (–1°C wet bulb temperature), or until 2060 to 2079 if snow can be made at a 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 relative changes in snowmaking conditions are at a similar range for future periods when using different wet bulb temperature thresholds. Regardless of the threshold used, approximately 20% and 50% reductions are projected for the near and far future periods, respectively.

6. References

Bhend J, Bathols J and Hennessy K 2012, *Climate change impacts on snow in Victoria*, CSIRO report for the Victorian Department of Sustainability and Environment, publications.csiro.au/rpr/pub?list=SEA&pid=csiro:EP117309&sb=RECENT&expert=false&n=12&rpp=25&page=1&tr=425&q=Hennessy&dr=all.

Chen J, Brissette FP, Poulin A and Leconte R 2011, Overall uncertainty study of the hydrological impacts of climate change for a Canadian watershed, *Water Resources Research*, vol.47 W12509.

Davis CJ 2013, Towards the development of long-term winter records for the snowy mountains, *Australian Meteorological and Oceanographic Journal*, vol.63, no.2, pp.303–314.

Di Luca AJ, Evans P and Ji F 2016, *Australian Snowpack: NARCliM ensemble valuation, statistical correction and future projections*, NARCliM Technical Note 7, NARCliM Consortium, Sydney, Australia, 88pp.

Di Luca AJ, Evans P and Ji F 2018, Australian snowpack in the NARCliM ensemble: evaluation, bias correction and future projections, *Climate Dynamics*, vol.51, no.1–2, pp.639–666.

Evans JP, Ekstrom M and Ji F 2012, Evaluating the performance of a WRF physics ensemble over South-East Australia, *Climate Dynamics*, vol.39, no.6, pp.1241–1258.

Evans JP, Ji F, Abramowitz G, Ekstrom M 2013a, Optimally choosing small ensemble members to produce robust climate simulations, *Environmental Research Letters*, vol.8.

Evans JP, Fita L, Argüeso D and Liu Y 2013b, Initial NARCliM evaluation, in Piantadosi J, Anderssen RS and Boland J (eds), *MODSIM2013, 20th International Congress on Modelling and Simulation*, Modelling and Simulation Society of Australia and New Zealand, December 2013, pp.2765–2771.

Evans J, Ji F, Lee C, Smith P, Argüeso D and Fita L 2014, Design of a regional climate modelling projection ensemble experiment–NARCliM, *Geoscientific Model Development,* vol.7, pp.621–629.

Fiddes SL, Pezza AB and Barras V 2015, A new perspective on Australian snow, *Atmospheric Science Letters*, vol.16, no.3, pp.246–252.

Fita L, Evans JP, Argüeso D, King AD and Liu Y 2016, Evaluation of the regional climate response to large-scale modes in the historical NARCliM simulations, *Climate Dynamics*, pp.1–15, doi: 10.1007/s00382-016-3484-x.

Harris RMB, Remenyi T and Bindoff NL 2016, *The potential impacts of climate change on Victoria Alpine Resorts*, a report for the Alpine Resorts Co-ordinating Council, Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart TAS.

Hennessy KJ, Whetton PH, Walsh K, Smith IN, Bathols JM, Hutchinson M and Sharples J 2008, Climate change effects on snow conditions in mainland Australia and adaptation at ski resorts through snowmaking, *Climate Research*, vol.35, no.3, pp.255–270.

IPCC 2000, *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*, published for the Intergovernmental Panel on Climate Change by Cambridge University Press, Cambridge, UK.

Ji F, Ekstrom M, Evans JP and Teng J 2014, Evaluating rainfall patterns using physics scheme ensembles from a regional atmospheric model, *Theoretical and Applied Climatology*, vol.115, pp.297–304.

Ji F, Evans JP, Teng J, Scorgie Y, Argüeso D and Di Luca A 2016, Evaluation of long-term precipitation and temperature WRF simulations for southeast Australia, *Climate Research*, vol.67, pp.99–115, DOI 10.3354/cr01366.

Nicholls N 2005, Climate variability, climate change and the Australian snow season, *Australian Meteorological Magazine*, vol.54, no.3, pp 177–185.

NIEIR (National Institute of Economic and Industry Research) 2006, *The economic significance of the Australian alpine resorts – summary report*, Alpine Resorts Co-ordinating Council.

OEH 2013, *Scientific Rigour Position Statement*, NSW Office of Environment and Heritage, www.environment.nsw.gov.au/-/media/OEH/Corporate-Site/Documents/Research/Our-science-and-research/oeh-scientific-rigour-position-statement-2013.pdf.

Pickering C 2007, 'Climate change and other threats in the Australian Alps', in M Taylor and P Figgis (eds): *Protected Areas: buffering nature against climate change*, WWF-Australia, Sydney, pp.28–34.

Ruddell AR, Budd WF, Smith IN, Keage PL and Jones R 1990, *The south east Australian alpine climate study*, a report by the Meteorology Department, University of Melbourne for the Alpine Resorts Commission.

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Duda MG, Huang XY, Wang W and Powers JG 2008, *A description of the advanced research WRF Version 3,* NCAR Technical Note, National Center for Atmospheric Research, Boulder Colorado, USA.

Slatyer R 2010, Climate change impacts on Australia's alpine ecosystems, *The ANU Undergraduate Research Journal*, vol.2.

Teng J, Vaze J, Chiew FHS, Wang B, Perraud J-M 2012, Estimating the relative uncertainties sourced from GCMs and hydrological models in modeling climate change impact on runoff, *Journal of Hydrometeorology*, vol.13, no.1, pp.122–139.

Timbal B, Ekstrom M, Fiddes SL, Grose M, Kirono DGC, Lim E, Lucas C and Wilson L 2016, *Climate change science and Victoria*, Bureau Research Report No. 14, 92pp.

Vaze J, Teng J and Chiew FHS 2011, Assessment of GCM simulations of annual and seasonal rainfall and daily rainfall distribution across south-east Australia, *Hydrological Processes*, vol.25, no.9, pp.1486–1497.

Whetton PH, Haylock MR and Galloway R 1996, Climate change and snow-cover duration in the Australian Alps, *Climatic Change*, vol.32, no.4, pp.447–479.