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Climate change impacts on snow in Victoria

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December 2012

www.cawcr.gov.au

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EXECUTIVE SUMMARY

In 2003, CSIRO and the Australian National University (ANU) published a report titled "The impact of climate change on snow conditions in mainland Australia". The key findings of this report included:

- Snow depths have declined from the 1950s to 2001;
- When projections from nine global climate models are used as input to a snow model, future decreases in snow depth, cover and duration are simulated;
- By 2020, the average annual duration of snow-cover decreases by between five and 48 days; maximum snow depths are reduced and tend to occur earlier in the year; and the total area covered in snow shrinks by 10-40%;
- Larger impacts are projected by 2050.

The aim of this report is to review and assess the latest evidence for (i) changes in Victorian snow properties up to 2011 and (ii) projected changes in snow properties up to the year 2050 based on 18 climate models. In contrast to the report published in 2003, this report does not cover changes in snow conditions in New South Wales (NSW), but focuses on changes in Victorian snow only.

The updated analysis of snow measurements at Rocky Valley Dam (altitude 1650 m) from 1954-2011 indicates a clear trend to lower maximum snow depths and an earlier end of the snow season. The long-term changes are superimposed on considerable year-to-year variability. The variability in maximum snow depth can be well explained by maximum temperature and precipitation from June to August. The earlier end of the snow season is clearly dependent on changes in temperature.

Temperature and precipitation projections from 18 climate models are used as input to the CSIRO snow model to estimate changes in snow conditions for 20-year periods centred on 2020 and 2050, relative to a 20-year period centred on 1990. Results are given for each climate model and a distinction is made between results for three different greenhouse gas emission scenarios: low (B1), medium (A1B) and high (A1FI).

This update confirms that the end of the snow season is likely to occur earlier in future, with a slightly later start, and lower maximum depths. These trends will be superimposed on large natural year-to-year variability. The number of good snow seasons is likely to decline while the number of poor seasons is likely to increase.

Decreases in maximum snow depth are evident in all simulations, but there is a wide range of uncertainty due to differences in projections between the 18 climate models. For example, at Falls Creek ski resort, the simulated average maximum depth is 150 cm in the 20-year period centred on 1990. By 2020, the average maximum depth decreases to 80-135 cm for the three different scenarios. By 2050, the average maximum depth decreases to 50-105 cm for the low scenario and 20-80 cm for the high scenario.

The area of north-east Victoria covered in snow declines in future. For example, between the 20-year periods centred on 1990 and 2020, the area averaging at least 1 day of snow-cover decreases by 10-40% across the three scenarios. Between the 20-year periods centred on 1990 and 2050, the area averaging at least 1 day of snow-cover decreases by 25-55% for the low scenario and 35-75% for the high scenario.

Across four ski resorts (Falls Creek, Mt Hotham, Mt Buller and Mt Buffalo), by 2020, the average snow season becomes 5-35 days shorter for the three scenarios. By 2050, the average snow season becomes 20-55 days shorter for the low scenario and 30-80 days shorter for the high scenario. Larger changes are likely at lower elevations, such as Mt Baw Baw and Lake Mountain, but projections for these sites were considered to be less robust.

This report has focused on projections averaged over 20-year periods. More attention needs to be paid to daily, monthly and annual variability in snow conditions, rather than 20-year averages. If the CSIRO snow model was upgraded to accept finer-resolution gridded daily data, then snow accumulation and ablation would be better simulated. The scope for adaptation through snow-making should be revisited, allowing for recent and projected improvements in the technology.

1. INTRODUCTION

In 2003, CSIRO and ANU published a report titled “The impact of climate change on snow conditions in mainland Australia” (Hennessy *et al.*, 2003). The key findings were:

- The alpine region in Victoria and New South Wales has become warmer and drier from 1950-2001;
- Snow depths have declined at sites with records from the 1950s to 2002;
- Simulations from nine global climate models, driven by a range of greenhouse gas and aerosol emissions scenarios, indicate that Victoria and New South Wales are likely to become warmer and drier in future;
- When these projections are used as input to a snow model, future decreases in snow depth, cover and duration are simulated;
- For a 20-year period centred on 2020, the average annual duration of snow-cover decreases by between five and 48 days; maximum snow depths are reduced and tend to occur earlier in the year; and the total snow-covered area shrinks by 10-40%. All projections were relative to a 20-year period centred on 1990;
- Larger impacts are projected for a 20-year period centred on 2050;
- One option to adapt to these changes is increased snow-making;
- Allowing for the decline in natural snow depths and the reduction in the frequency of temperatures cold enough for snow-making, the number of snow guns required to achieve target snow-depth profiles was estimated. The increase in the number of snow guns required by 2020 is between 11 and 200%, with a mid-range estimate of about 100%.

The aim of this report is to review and assess the latest evidence for changes in Victorian snow properties up to 2011 and projected changes in snow properties up to the year 2050 based on 18 climate models. Changes in other Australian alpine regions, and the scope for adaptation through snow-making, are not addressed.

2. OBSERVED TRENDS

2.1 Trends in snow properties

Rocky Valley Dam snow course (altitude 1650 m) is the only high-quality snow measurement site in the Victorian Alps with constant long-term measurements free of artificial influences (such as snow-making). These measurements cover the period from 1954 to 2011 with missing data in 1973 due to insufficient snow cover for measurements. Snow depth and snow density have been observed fortnightly (weekly from 1997 onwards). The record of snow depths is compiled from two different sources: from data provided by the State Electricity Commission of Victoria for data up to 1989 and from AGL Hydro from 1969 to 2011. Individual measurements differ slightly in the period with overlap; we use the data provided by AGL Hydro from 1969 due to consistency in the most recent period.

Maximum snow depth at Rocky Valley Dam is highly variable from year to year (Figure 1), ranging from 33 cm in 2006 to 270 cm in 1964. The start and end of the snow season in each year are defined by the date of the first and last snow measurements. The tendency towards lower maxima and an earlier end of the snow season are evident in Figure 1 and in decadal snow profiles (Figure 2). For example, while the 2011 snow season started fairly early and reached high snow depths in the beginning of the season, lack of precipitation and the warmth in the second half of winter caused the low snow depths observed towards the end of the season.

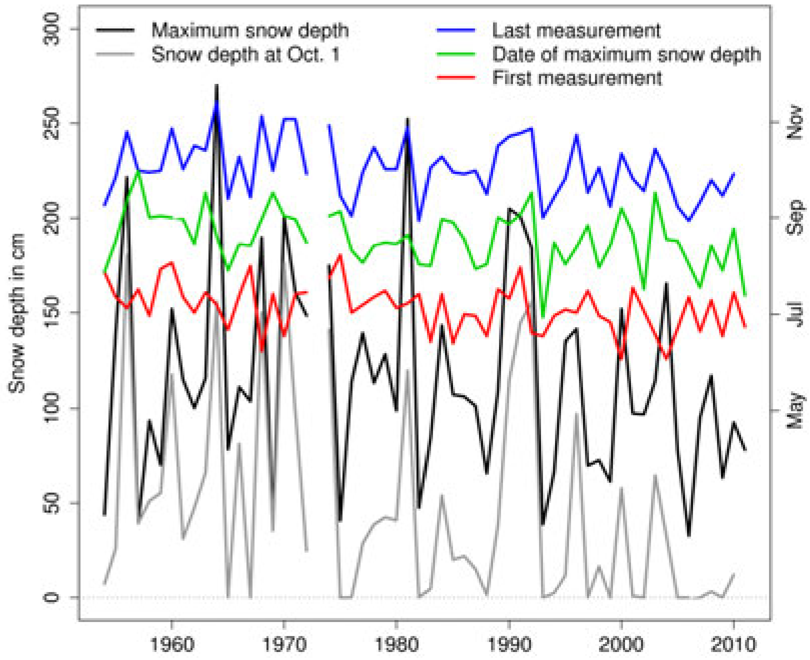


Figure 1: Maximum snow depth (black line) and snow depth at October 1st (grey line) at Rocky Valley Dam from 1954 to 2011, along with the date of the maximum snow depth (green line), first measurement (red line) and last measurement (blue line).

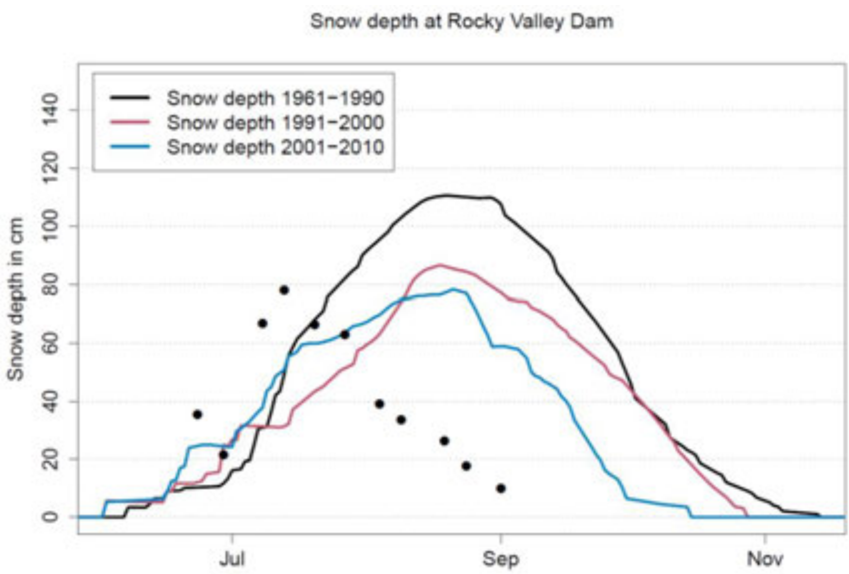


Figure 2: Snow depth profile at Rocky Valley Dam averaged over three periods: 1961-1990, 1991-2000 and 2001-2010. Snow depths have been linearly interpolated in between measurements. The measurements during 2011 are shown as black dots.

Maximum snow depth has declined, with the most recent periods contributing most to the trend from 1954 to 2011 (Table 1). However, the variability in maximum snow depth is large, so short-term trends can be strongly influenced by individual years. It is obvious from the time series in Figure 1 that years with large maximum snow depth are missing in the past two decades. This contributes to the negative trend in maximum snow depth.

The different characteristics of changes throughout the snow season become apparent when looking at changes in snow depths at fixed dates. There is a slight increase or little trend early in the snow season, contrasted with a strong decrease late in the snow season. Changes in snow depth at the beginning of September and October are statistically significant, whereas the slight increase early in the season is not.

Given that the first and last measurements at Rocky Valley Dam provide a good estimate of the duration of the snow season, there is a clear trend to an earlier start and earlier end of the snow season throughout the record (Table 1). As with maximum snow depth, the most recent decades show the strongest change. The rate of change in the end of the snow season is larger than the rate of change in the start of the snow season, indicating a reduction in the duration of the snow season as well.

Table 1: Trends in snow properties at Rocky Valley Dam for 1954-2011, 1969-2011, 1979-2011 and 1989-2011. Trends are given for maximum snow depth (Max depth) and snow depth at fixed dates during the snow season (Depth Jun01, Depth Jul01, Depth Aug01, Depth Sep01, Depth Oct01) in cm per decade. Also shown are trends in start of season, date of maximum snow depth (Max date), and end of season in days per decade. Trends in June-September mean daily maximum temperature (Tmax JJAS) are in ^{o}C per decade and trends in June-September precipitation (Precip JJAS) are in mm per decade. The uncertainty estimates denote ± 2 standard deviations about the central estimate, corresponding to a 95% confidence interval. Statistically significant trends are marked in bold.

	1954-2011	1969-2011	1979-2011	1989-2011
Max depth	-5.7 ± 8.5	-10.9 ± 12.6	-14.2 ± 18	**-29.8 ± 28.6**
Depth Jun01	0.4 ± 2	1.3 ± 2.5	0.8 ± 4.1	1.9 ± 8.1
Depth Jul01	1.2 ± 4.1	0.9 ± 6.5	-3.9 ± 9.8	-0.7 ± 15.7
Depth Aug01	-6.4 ± 6.5	-6.2 ± 9.7	-6.5 ± 13.9	2.6 ± 23.9
Depth Sep01	**-11.4 ± 9.3**	**-18 ± 14.7**	-21.4 ± 21.5	**-43.1 ± 34**
Depth Oct01	**-11.1 ± 8.2**	**-14.7 ± 12.4**	-14.7 ± 16.9	**-42.5 ± 28.8**
Season start	**-3.6 ± 2.2**	**-4.2 ± 3.5**	-3 ± 5.1	-5.8 ± 9.1
Max date	**-3.9 ± 2.7**	**-4.7 ± 4.4**	-3.4 ± 6.7	-9.8 ± 12.7
Season end	**-3.4 ± 2.9**	**-5.3 ± 4.6**	-5.7 ± 6.4	**-13.6 ± 11.1**
Tmax JJAS	0.1 ± 0.1	0.2 ± 0.2	**0.3 ± 0.2**	**0.6 ± 0.4**
Precip JJAS	-37.5 ± 41.6	-57.4 ± 63.4	**-104.5 ± 90.6**	**-178.4 ± 147.2**

2.2 Trends in temperature and precipitation

Monthly precipitation data and mean daily maximum and minimum temperature data were compiled on a 5 km grid as part of the Australian Water Availability Project (AWAP; Jones *et al.*, 2009). It is important to note that very few climate stations at high elevations are available, so temperature and precipitation values in the AWAP dataset at higher altitudes are mainly extrapolated from lower lying stations.

In the period from 1954 to 2011, a decrease in precipitation occurred at Rocky Valley Dam (Table 1) and throughout the Victorian Alps (not shown). While precipitation has increased slightly in July mainly in lower-altitude areas to the northwest of the main Divide, a marked drying is apparent in the latter part of the snow season with a maximum drying in August in the western part of the Victorian Alps (Figure 3).

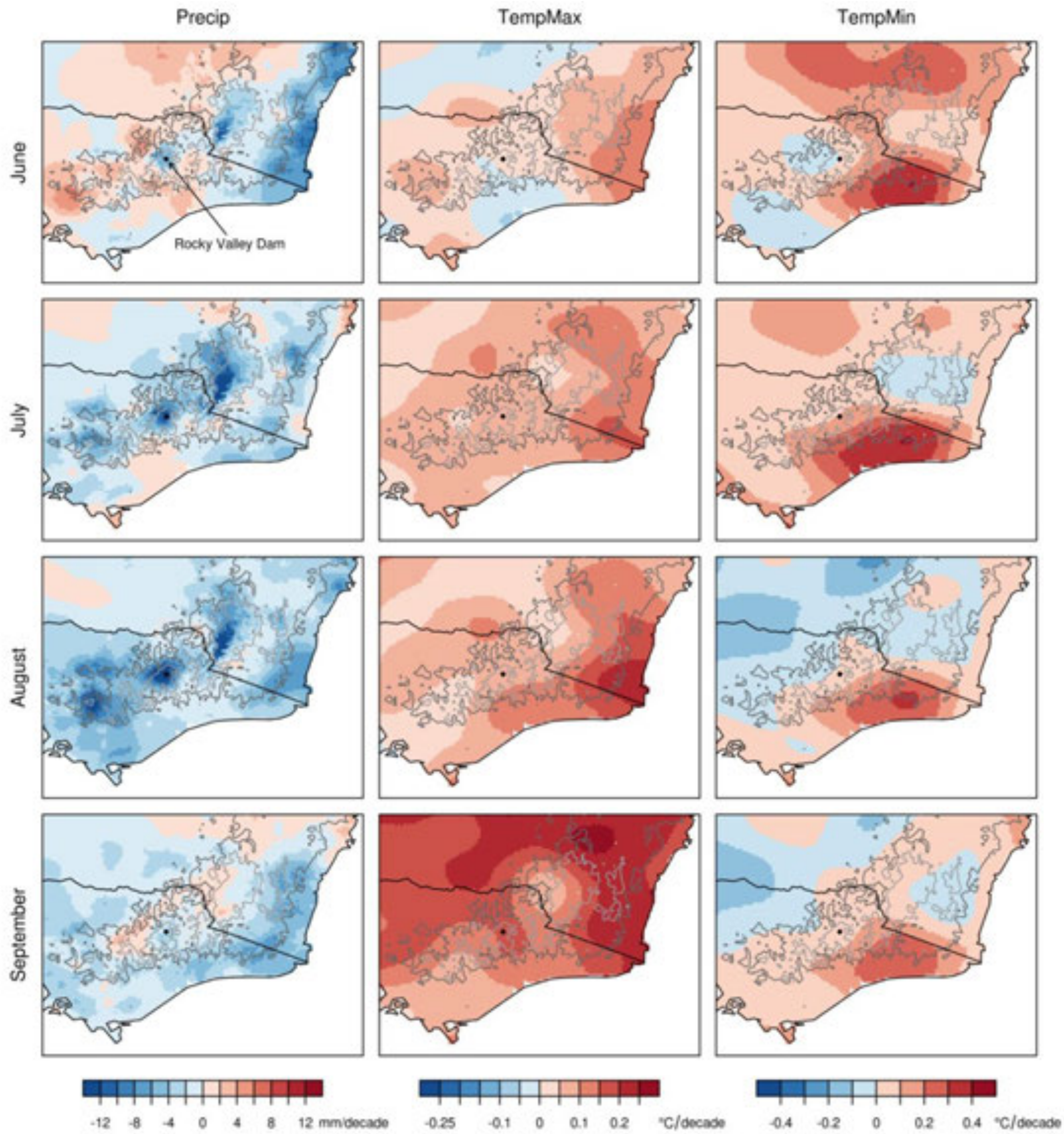


Figure 3: Observed trends from 1954 to 2011 in precipitation and maximum and minimum temperature, based on AWAP data (Jones et al., 2009).

Near-surface mean daily maximum and minimum temperatures show either warming or little change throughout the snow season (Figure 3). The increase in maximum temperatures is strongest towards the end of the snow season in September, whereas changes in maximum temperature in June to August are moderate to small. Minimum temperature shows a strong warming in south-east Gippsland throughout the snow season. Due to the higher spatial correlation for temperature, the trend map is smoother. There is no obvious effect of altitude on temperature trends. Whether changes in temperature are actually independent of altitude or whether this is an artefact of the AWAP interpolation method is not clear.

In contrast, there is a clear dependence of trends in precipitation with altitude in July and August (Figure 4). The observed drying in lower-lying areas of the Victorian Alps is considerably smaller than at high-elevation sites. Altitude dependency of changes in precipitation in both June and September is rather small.

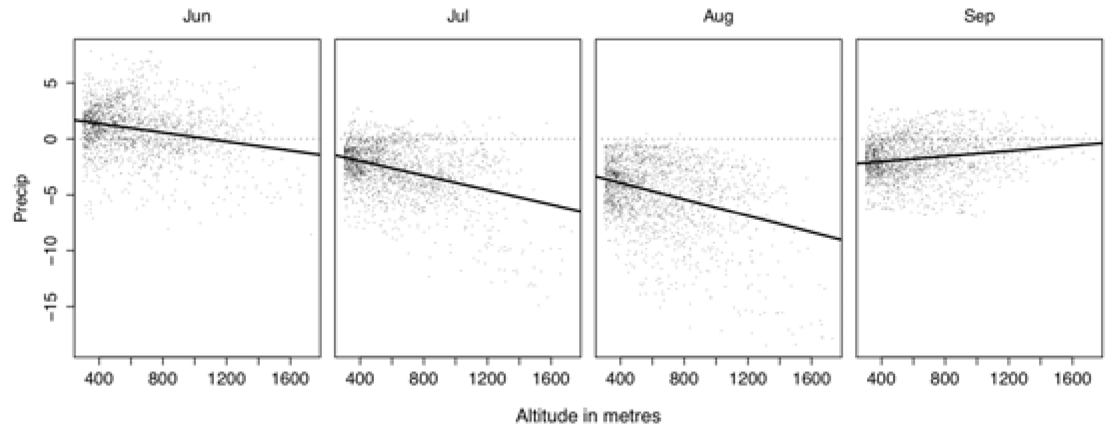


Figure 4: Trends from 1954 to 2011 in precipitation (mm per decade) relative to altitude (metres). The black line denotes a least square fit through the data points and indicates a potential altitude dependency of changes in the respective months (Jun, Jul, Aug, Sep).

2.3 Relationships between snow, temperature and precipitation

Both maximum snow depth and the end of the snow season are significantly correlated with both temperature and precipitation during June to August. Furthermore, maximum snow depth correlates strongly with the end of the snow season (as characterized by the last snow measurement). The start of the snow season, in contrast, correlates neither with maximum temperature nor with precipitation. Additional analysis reveals that the start of the snow season is not related to maximum temperature or precipitation in any month in the run-up to the snow season. Whether this is an artefact of measurement practice at the site or a real feature is unclear.

A linear regression model was developed to assess links between maximum snow depth and June to August (JJA) maximum temperature and precipitation. Both temperature and precipitation contribute significantly to explaining variability in maximum snow depth. The two predictors together explain 57% of the variance in maximum snow depth.

Similar to maximum snow depth, we model the end of the snow season using June to September (JJAS) maximum temperature and precipitation. In contrast to maximum snow depth, precipitation is less important in explaining variability in the end of the snow season. Although the end of the snow season strongly correlates with maximum snow depth, snow melt and thus the end of the snow season seem to be more strongly influenced by temperature. The two predictors explain 64% of the variance in the end of the snow season at Rocky Valley Dam.

The individual contributions of changes in temperature and precipitation to the overall trends in maximum snow depth and the start and end of the snow season have been assessed using partial regression (Figure 5), i.e. through the covariance of temperature (precipitation) with the respective snow indicator after removing the linear effect of precipitation (temperature) from both variables. The individual contributions isolate temperature and precipitation impacts on snow that are independent of each other.

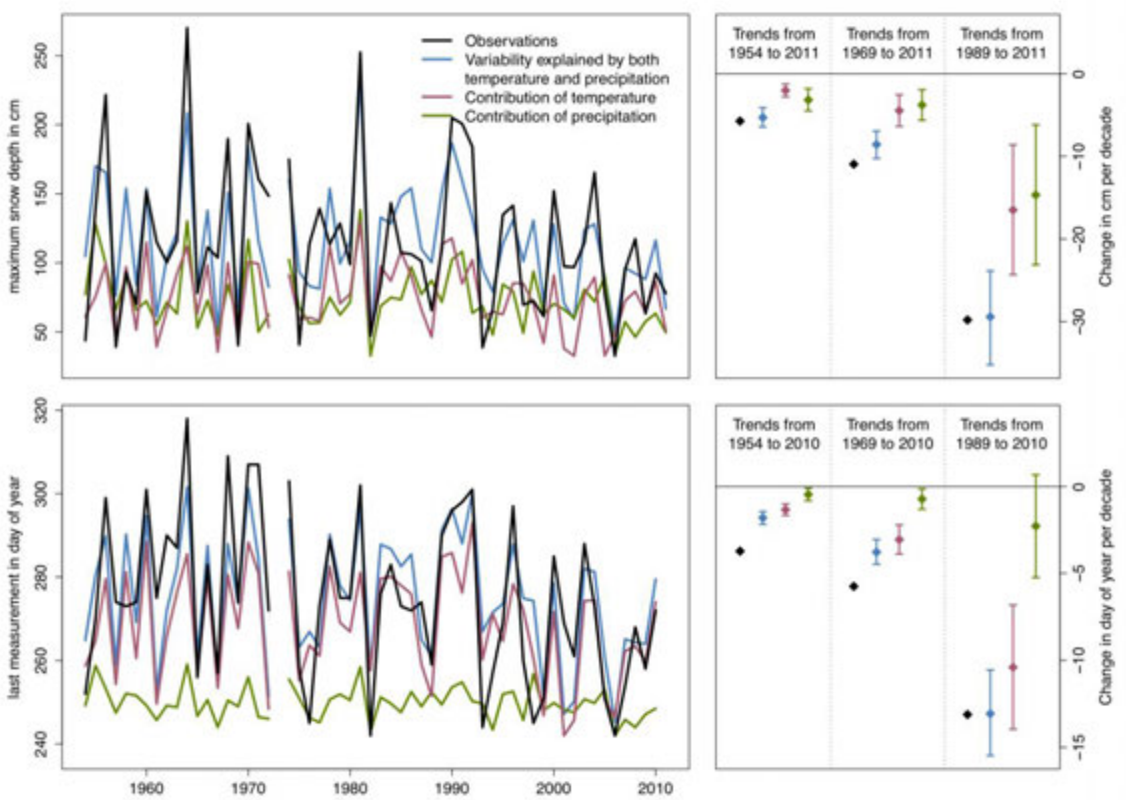


Figure 5: Upper panels: Linear regression of maximum snow depth on Jun-Aug mean daily maximum temperature and precipitation (left), and its respective contributions to trends from 1954 to 2011 (right). Lower panels: Accordingly for the end of the snow season and maximum temperature and precipitation in Jun-Sep. The time series of individual contributions (red and green lines) have been offset for better display. The diamond in the panels to the right indicates the central estimate, the corresponding bars indicate the 95% confidence interval including estimation uncertainty of the linear model and the partial regression model.

Over the period from 1954 to 2011, the observed trend in maximum snow depth at Rocky Valley Dam is -6 cm per decade. The decrease in precipitation contributes -3 ± 1 cm per decade and the increase in temperature contributes -2 ± 1 cm per decade to the overall change of -5 ± 1 cm per decade attributable to temperature and precipitation changes. For trends over 1969 to 2011 and 1989 to 2011, the rate of change increases, but the relative contributions of temperature and precipitation remain comparable in shorter periods.

The observed variability in the start of the snow season as defined by the first measurement at Rocky Valley Dam is basically uncorrelated with temperature and precipitation variability in the preceding months (not shown). This and the fact that the start of the measurements occurs at vastly varying snow heights (see Figure 6) suggest that the first measurement is not a reliable indicator of the start of the snow season. Therefore, attempting to explain variability in the onset of the snow season in the Victorian Alps is not pursued any further. The tendency towards an earlier onset of the snow season, however, might still be a real feature of snow cover variability, as measurements in New South Wales indicate consistent trends towards an earlier onset as well (not shown).

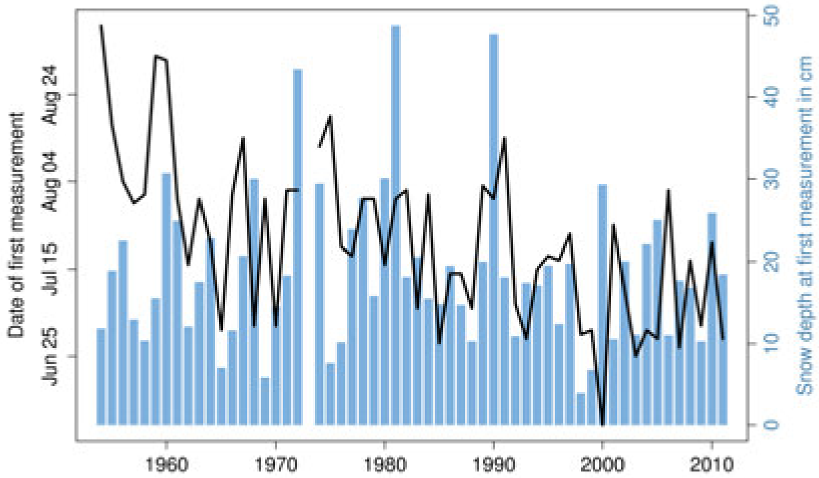


Figure 6: Date of the first measurement at Rocky Valley Dam from 1954 to 2011 (black line) along with the snow depth in cm recorded at the first measurement (blue bars).

Of the observed trend in the end of the snow season of -3.4 days per decade, -1.8 ± 0.3 days per decade are attributable to changes in temperature and precipitation according to the linear model. In contrast to changes in maximum snow depth, the partial contribution of precipitation variability unrelated to temperature variability is smaller, so most of the change in the end of the snow season is due to the observed warming. Since global and regional changes in temperature since the mid-20th century are partly attributable to anthropogenic increases in greenhouse gases (Stott *et al.*, 2010), it is reasonable to conclude that part of the earlier end to the snow season is also anthropogenic.

2.4 Conclusions

Snow depths and the start/end of the snow season in Victoria are highly variable from year to year. However, snow measurements at Rocky Valley Dam from 1954-2011 indicate a clear trend to lower maximum snow depths and an earlier end of the snow season. This corroborates earlier findings of changes in snow in the Australian Alps (Nicholls, 2005; Hennessy *et al.*, 2008).

The variability in maximum snow depth can be well explained by maximum temperature and precipitation from June through to August, with changes in temperature and precipitation contributing in roughly equal parts. This, together with the altitude dependency of changes in precipitation, suggests that the decrease in maximum snow depth is slightly stronger at higher altitudes. However, conclusions from the linear regression model may not be applicable to snow depth at lower sites, as the processes governing snow cover at lower altitudes are likely different.

The observed trend towards an earlier end of the snow season is dependent on changes in temperature. Since the warming is partly due to anthropogenic increases in greenhouse gases, it is reasonable to conclude that part of the earlier end to the snow season is also anthropogenic.

3. PROJECTED CHANGES IN SNOW CONDITIONS

3.1 Data and method

In the 2003 report titled "The impact of climate change on snow conditions in mainland Australia", seasonal-mean temperature and precipitation projections were based on simulations from nine global climate models, driven by a range of greenhouse gas and aerosol emissions scenarios (IPCC, 2000). These projections were used as input to the CSIRO snow model to estimate changes in snow conditions for 20-year periods centred on 2020 and 2050, relative to a 20-year period centred on 1990. Ranges of uncertainty encompassed results from different emission scenarios and the nine different global climate models, but results for individual emission scenarios and models were not shown. The data and methods are described in Hennessy *et al.* (2003; 2008).

In 2007, updated climate change projections for Australia were published (CSIRO and BoM, 2007), based on 23 climate models used in the IPCC (2007) report. CSIRO has more confidence in the updated projections than the previous projections as they are based on a larger number of more advanced climate models. These projections have not previously been used in an assessment of snow impacts.

One of the aims of this report is to use the updated projections in a snow impact assessment. A recent evaluation of the ability of climate models to simulate the current climate in the Pacific region found that 18 were most suitable for projections (Irving *et al.*, 2011). In the absence of an equivalent evaluation for Victoria, this set of 18 models is also likely to be suitable for projections over Victoria. Therefore, monthly-mean temperature and precipitation projections in this study are based on those 18 models. Additional details on each of the models can be found at the PCMDI website (www.pcmdi.llnl.gov) and in Table 8.1 of Randall *et al.* (2007).

Temperature and precipitation projections are used as input to the CSIRO snow model to estimate changes in snow conditions for 20-year periods centred on 2020 and 2050, relative to a 20-year period centred on 1990. In the 2003 study, winter-spring-mean projections were used, whereas in the current study monthly-mean projections are used. Results are given for each climate model and a distinction is made between results for three different emission scenarios: low (B1), medium (A1B) and high (A1FI). Due to the different emissions trajectories in the near future, the medium (A1B) scenario results in a stronger response in 2020 than the low and high scenarios (Figure 7). By 2050 the response to the different scenarios is as expected with the high (A1FI) scenario resulting in the strongest change. For carbon dioxide (CO_2), emissions have been tracking above the middle of the IPCC range since 2005, with a dip in 2009 due to the global financial crisis (Figure 7). The US Department of Energy estimates that emissions rose 6% in 2010, effectively continuing the pre-2009 trend.

Results are presented for the north-east Victorian region for snow depth, area and duration. At four ski resorts (Falls Creek, Mt Hotham, Mt Buller and Mt Buffalo), average depth profiles are plotted, and maximum depths and durations are tabulated. Snow simulations for Baw Baw and Lake Mountain were not considered robust, for reasons outlined in Appendix 1 of the 2003 report, so they are not presented.

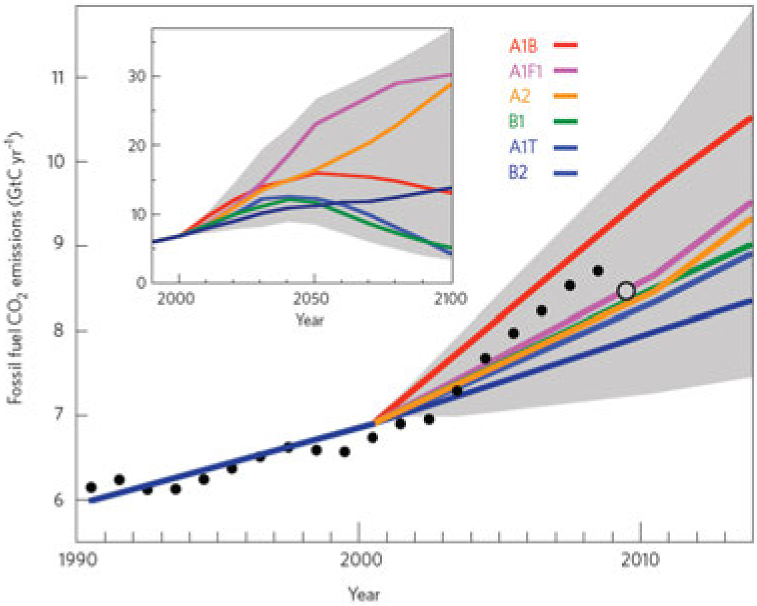


Figure 7: CO_2 emissions (Gt/year) from 1990-2009 (black dots) compared with IPCC scenarios (grey shading shows the full range, while coloured lines show six "marker" scenarios). The open circle shows an estimate for 2009 which includes the effect of the global financial crisis. The inset plot shows IPCC emission scenarios from 1990-2100. Source: Manning et al (2010).

3.2 Snow depth and duration

Simulated annual-average maximum snow depths for 20-year periods centred on 1990 and 2020 for medium (A1B) emissions are shown in Figure 8. Decreases are evident in all simulations, but there is a wide range of uncertainty due to differences in climate projections between the 18 models. For example, at Falls Creek, the average maximum depth decreases from 150 cm in the 20-year period centred on 1990 to 90-135 cm for the low (B1) scenario and to 95-135 cm for the high (A1FI) scenario in 2020 (Table 2). These projected trends will be superimposed on large natural year-to-year variability. The number of good snow seasons is expected to decline while the number of poor seasons is likely to increase.

Table 2: Simulated annual-average maximum snow-depth (cm) at four ski resorts for 20-year periods centred on 1990 and 2020 for low (B1), medium (A1B) and high (A1FI) emission scenarios. The range of depths represents the spread of results from 18 climate models. Simulated snow-depths have been rounded to the nearest 5 cm.

Site	1980-1999	2010-2029 low	2010-2029 medium	2010-2029 high
Falls Creek	150	90-135	80-130	95-135
Mt Hotham	130	80-115	75-115	85-115
Mt Buller	95	50-80	45-80	50-80
Mt Buffalo	60	20-45	20-45	20-45

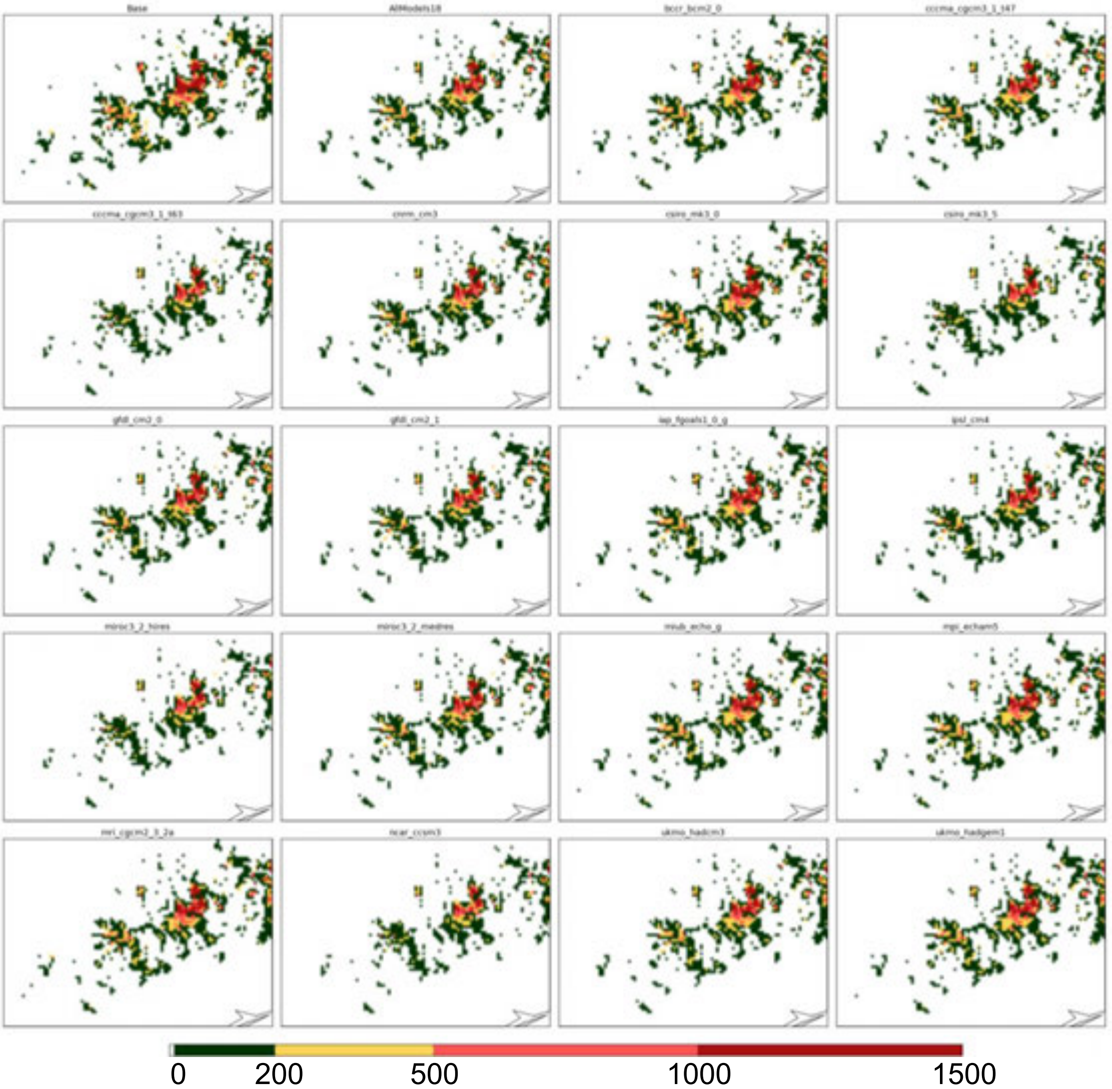


Figure 8: Average maximum snow-depth (mm) over north-east Victoria (Lat -38.0 to -36.25º S, Lon 145.5 to 148.0º E) for 20-year periods centred on 1990 (top-left "base" case) and 2020 (medium-A1B emissions scenario) for 18 climate models. The 18-model average pattern is shown in the top row, next to the "base" case.

Table 3: Simulated annual-average maximum snow-depth (cm) at four ski resorts for 20-year periods centred on 1990 and 2050 for low (B1), medium (A1B) and high (A1FI) emission scenarios. The range of depths represents the spread of results from 18 climate models. Simulated snow-depths have been rounded to the nearest 5 cm.

Site	1980-1999	2040-2059 low	2040-2059 medium	2040-2059 high
Falls Creek	150	50-105	30-90	20-80
Mt Hotham	130	40-95	25-80	15-70
Mt Buller	95	20-60	10-50	5-45
Mt Buffalo	60	10-30	5-25	0-20

The decreases in maximum snow depth are larger in 2050 (Figure 9) and there is greater sensitivity to the different emission scenarios (see maps for low-B1 and high-A1FI in Appendix 1). Decreases in depth are small for the low (B1) scenario, moderate for the medium (A1B) scenario and substantial for the high (A1FI) scenario. For example, at Falls Creek, the average maximum depth decreases from 150 cm in the 20-years centred on 1990 to 50-105 cm in 2050 for the low (B1) scenario and 20-80 cm for the high (A1FI) scenario (Table 3).

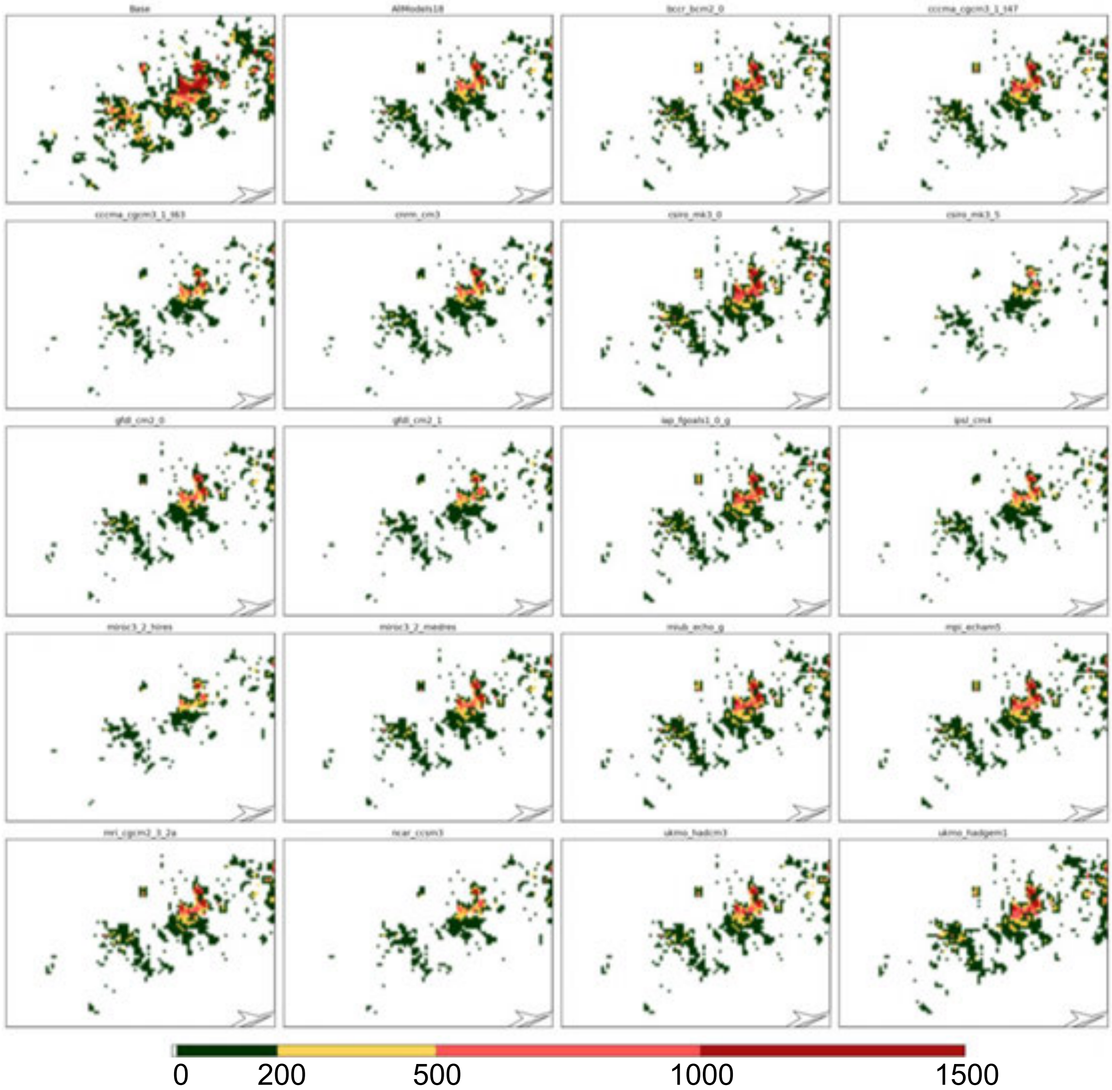


Figure 9: Average maximum snow-depth (mm) over north-east Victoria (Lat -38.0 to -36.25º S, Lon 145.5 to 148.0º E) for 20-year periods centred on 1990 (top-left) and 2050 (medium-A1B emissions scenario) for 18 climate models. The 18-model average pattern is shown in the top row, next to the "base" case. Corresponding maps for the B1 and A1FI emission scenarios are in Appendix 1.

Snow depth profiles show how the daily depths change during a snow season, starting with low depths in early June, peaking in August, then declining from September to November. Profiles averaged over 20-year periods centred on 1990, 2020 and 2050 for the medium (A1B) scenario indicate that the end of the snow season is likely to occur earlier in future, with a slightly later start, and lower maximum depths (Figures 10-13). Profiles for the low (B1) and high (A1FI) scenarios for 2020 and 2050 are presented in Appendix 2.

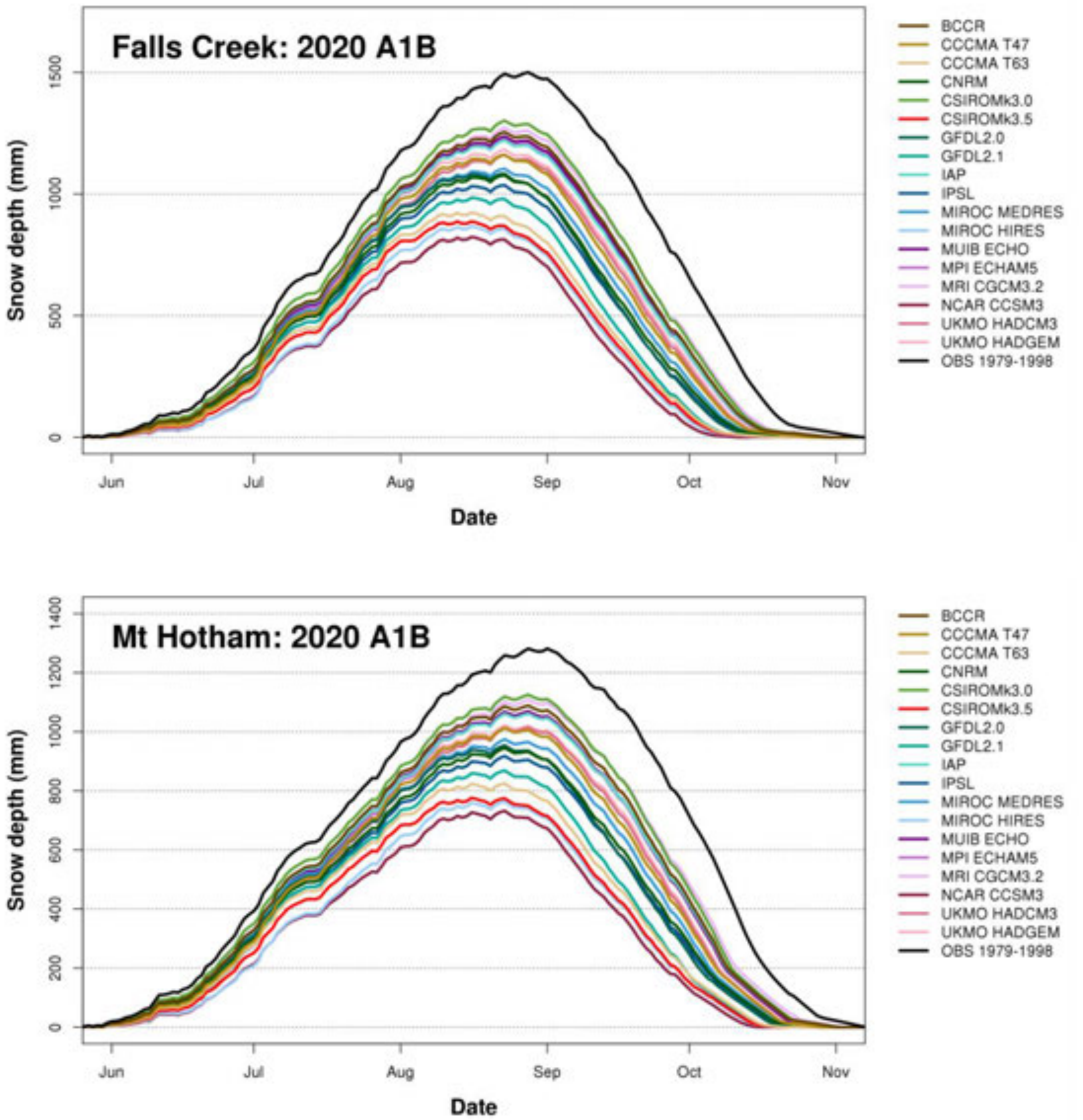


Figure 10: Simulated snow depth profiles for 20-year periods centred on 1990 (black line) and 2020 (coloured lines) for 18 climate models and the medium (A1B) emissions scenario at Falls Creek and Mt Hotham.

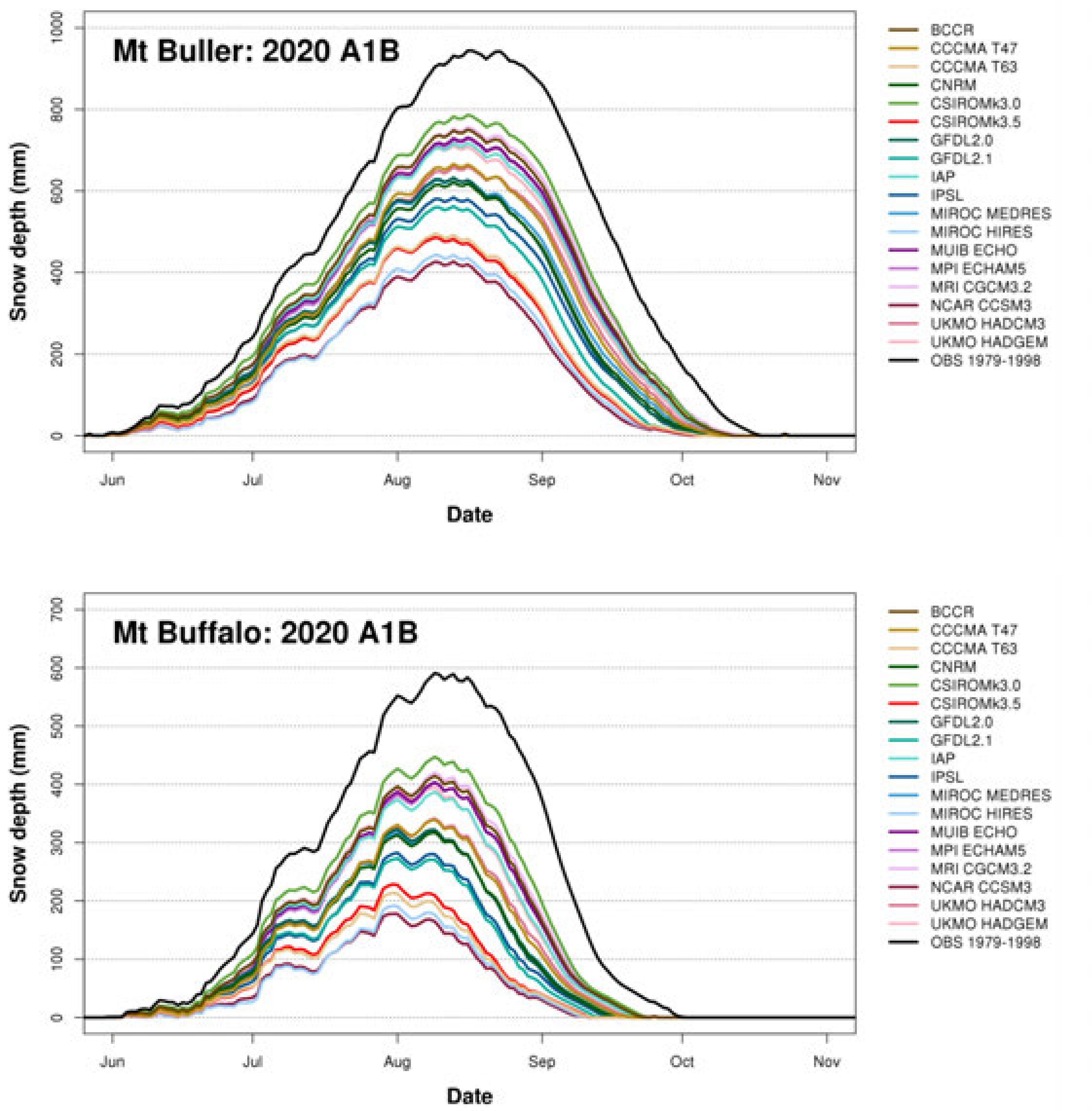
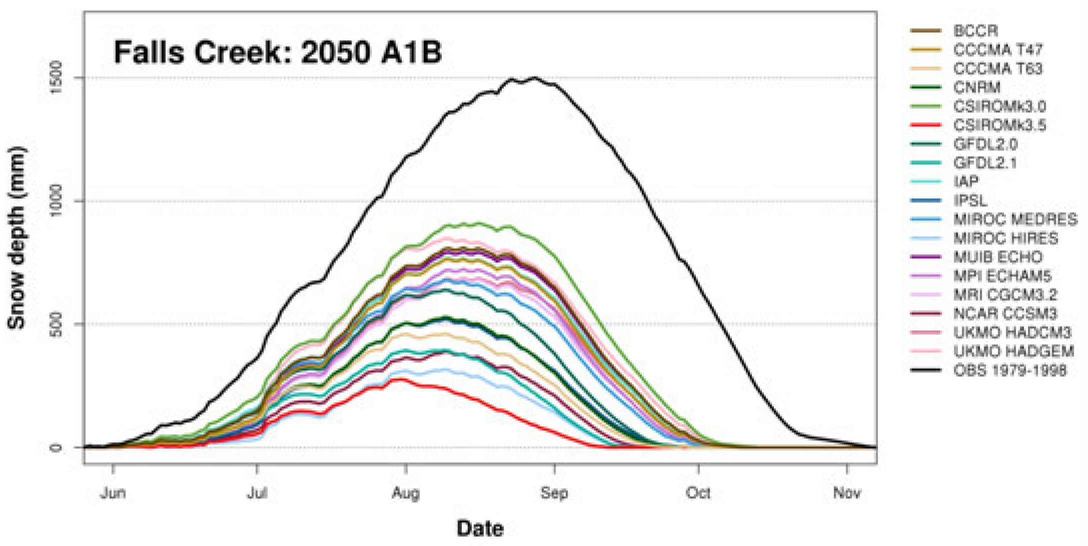


Figure 11: Simulated snow depth profiles for 20-year periods centred on 1990 (black line) and 2020 (coloured lines) for 18 climate models and the medium (A1B) emissions scenario at Mt Buller and Mt Buffalo.



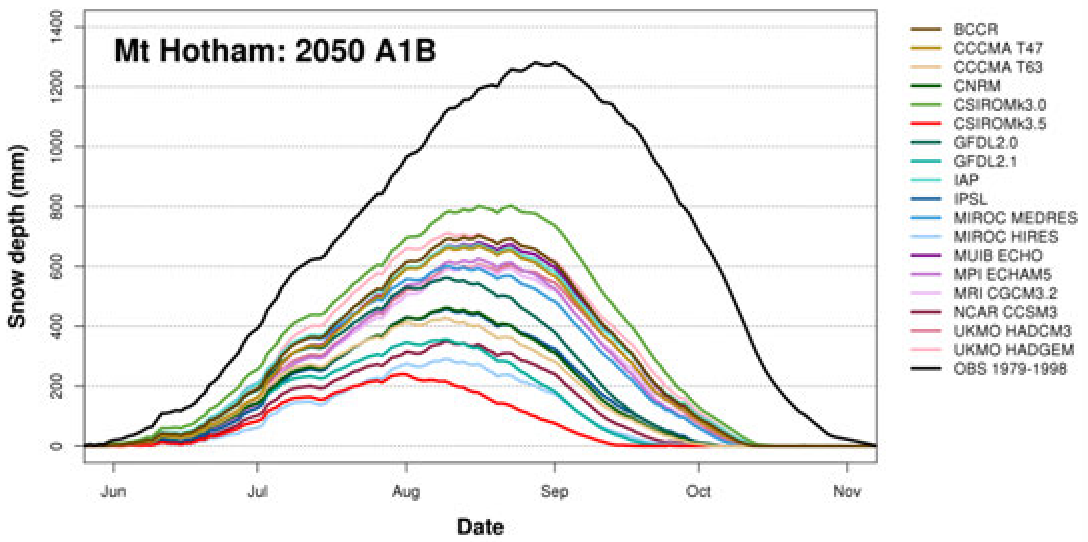


Figure 12: Simulated snow depth profiles for 20-year periods centred on 1990 (black line) and 2050 (coloured lines) for 18 climate models and the medium (A1B) emissions scenario at Falls Creek and Mt Hotham.

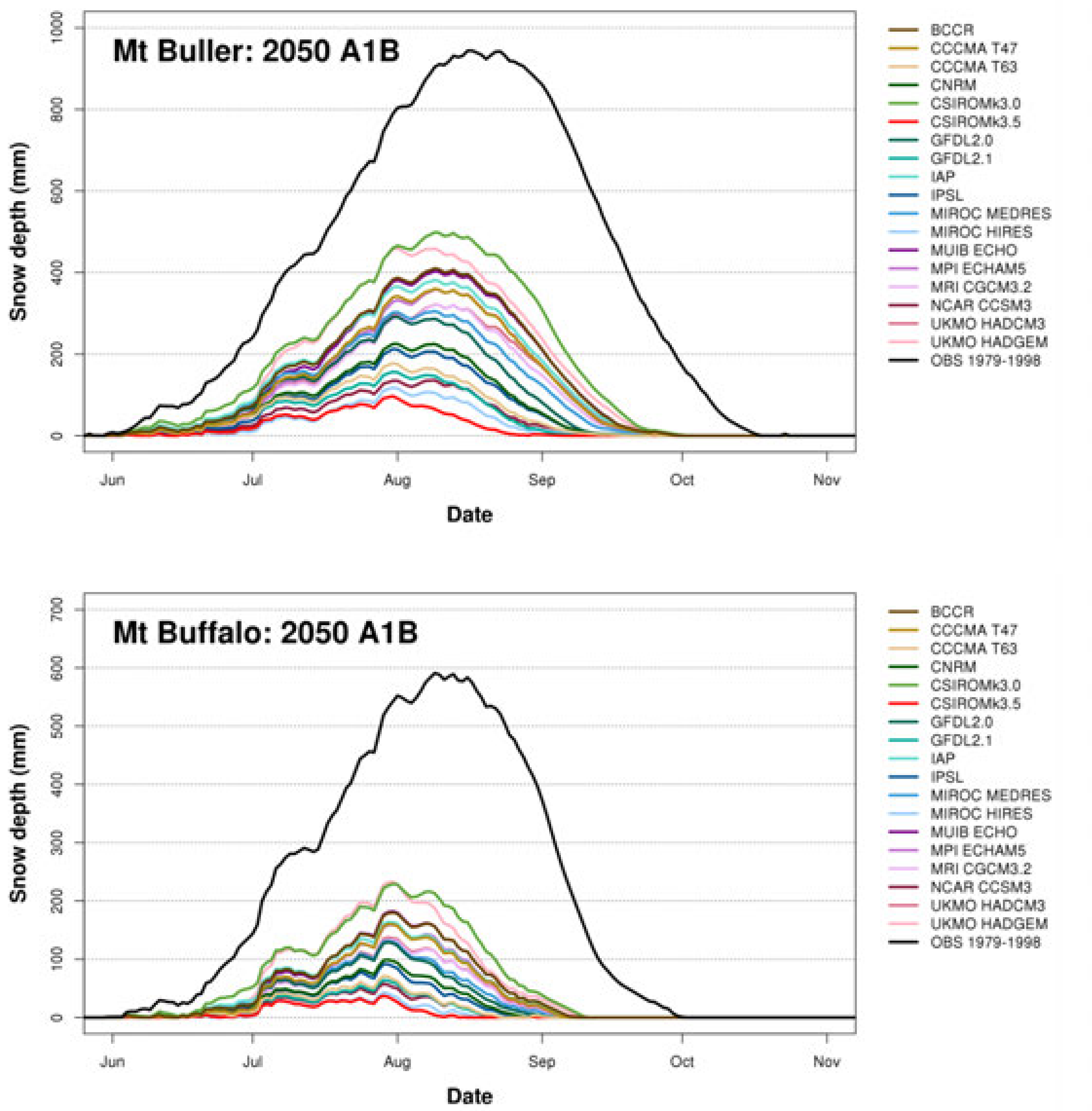


Figure 13: Simulated snow depth profiles for 20-year periods centred on 1990 (black line) and 2050 (coloured lines) for 18 climate models and the medium (A1B) emissions scenario at Mt Buller and Mt Buffalo.

Simulated annual-average snow-cover durations for 20-year periods centred on 1990 and 2020 are shown in Figure 14 and Table 4. The area averaging at least 1 day of snow-cover decreases by 10-35% for the low (B1) and high (A1FI) scenarios and by 15-40% for the medium scenario (A1B). Smallest (largest) decreases are simulated by the HadGEM1 (MIROC3.2-HIRES) model. It is important to note that the report published in 2003 lists projected snow area decreases for New South Wales and Victoria, whereas this report focuses on changes in Victorian snow only. Therefore, corresponding results of the two reports relating to changes in snow-cover extent are not directly comparable. Decreases in duration are more obvious for the 20-year period centred on 2050 (Figure 15). For example, the area averaging at least 1 day of snow-cover decreases by 25-55% for the low (B1) scenario, 30-70% for the medium (A1B) scenario and 35-75% for the high (A1FI) scenario (Table 5). The area averaging at least 60 days of snow-cover decreases by 45-80% for the low (B1) scenario, 55-90% for the medium (A1B), and 60-95% for the high (A1FI) scenario.

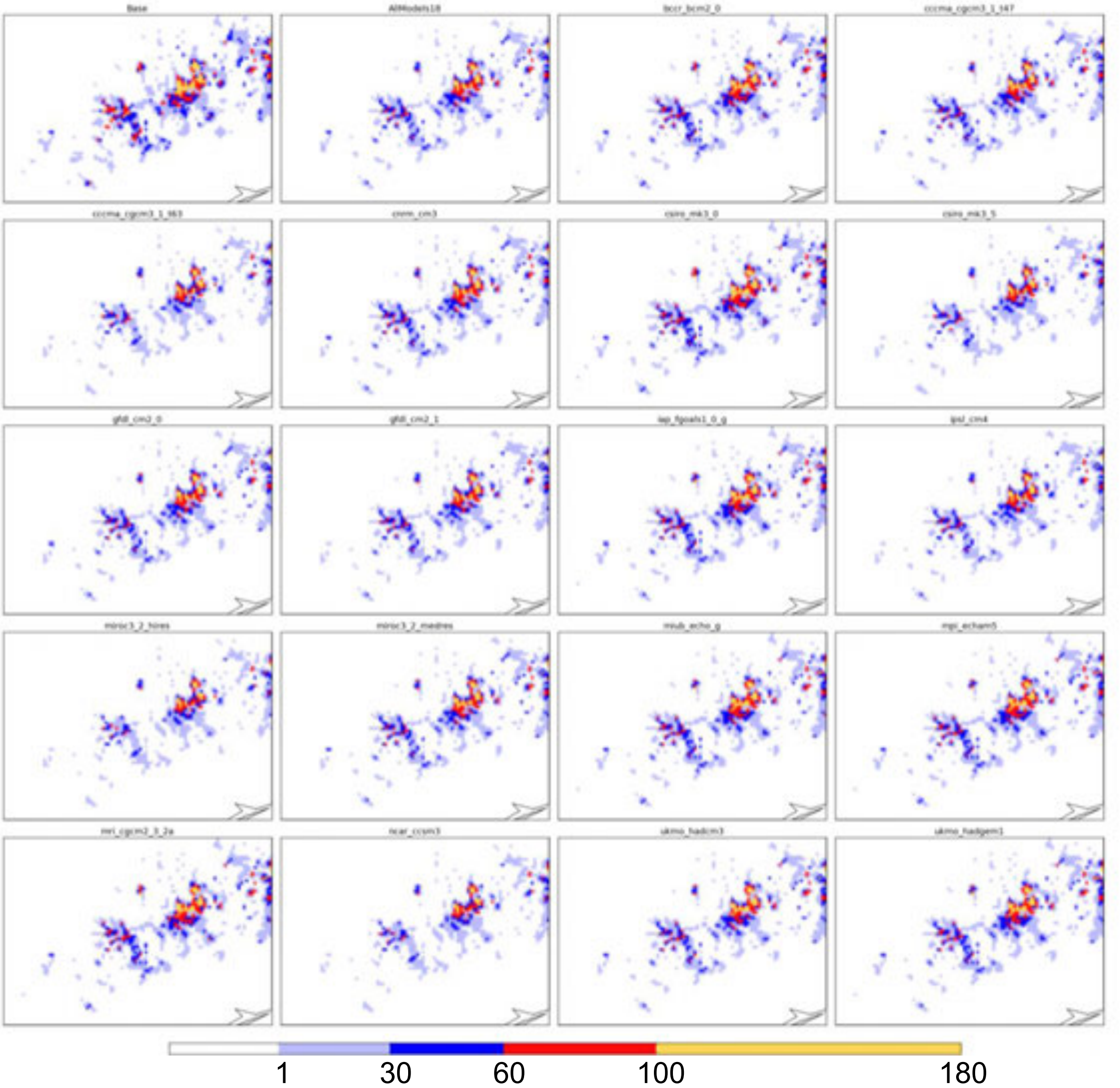


Figure 14: Average snow-cover duration (number of days with at least 1 cm of snow) over north-east Victoria for a 20-year period centred on 1990 (top-left) and a 20-year period centred on 2020 (medium-A1B emissions scenario) for 18 climate models. The 18-model average pattern is shown in the top row, next to the "base" case.

Table 4: Simulated percentage changes in the area of north-east Victoria with at least 1, 30 or 60 days annual-average snow-cover duration for 20-year periods centred on 2020 for three emissions scenarios: low (B1), medium (A1B) and high (A1FI). The range of changes represents the spread of results from 18 climate models. Simulated changes have been rounded to the nearest 5%.

Snow duration	2010-2029 low	2010-2029 medium	2010-2029 high
At least 1 day	-10% to -35%	-15% to -40%	-10% to -35%
At least 30 days	-15% to -50%	-20% to -55%	-15% to -50%
At least 60 days	-15% to -55%	-20% to -60%	-15% to -55%

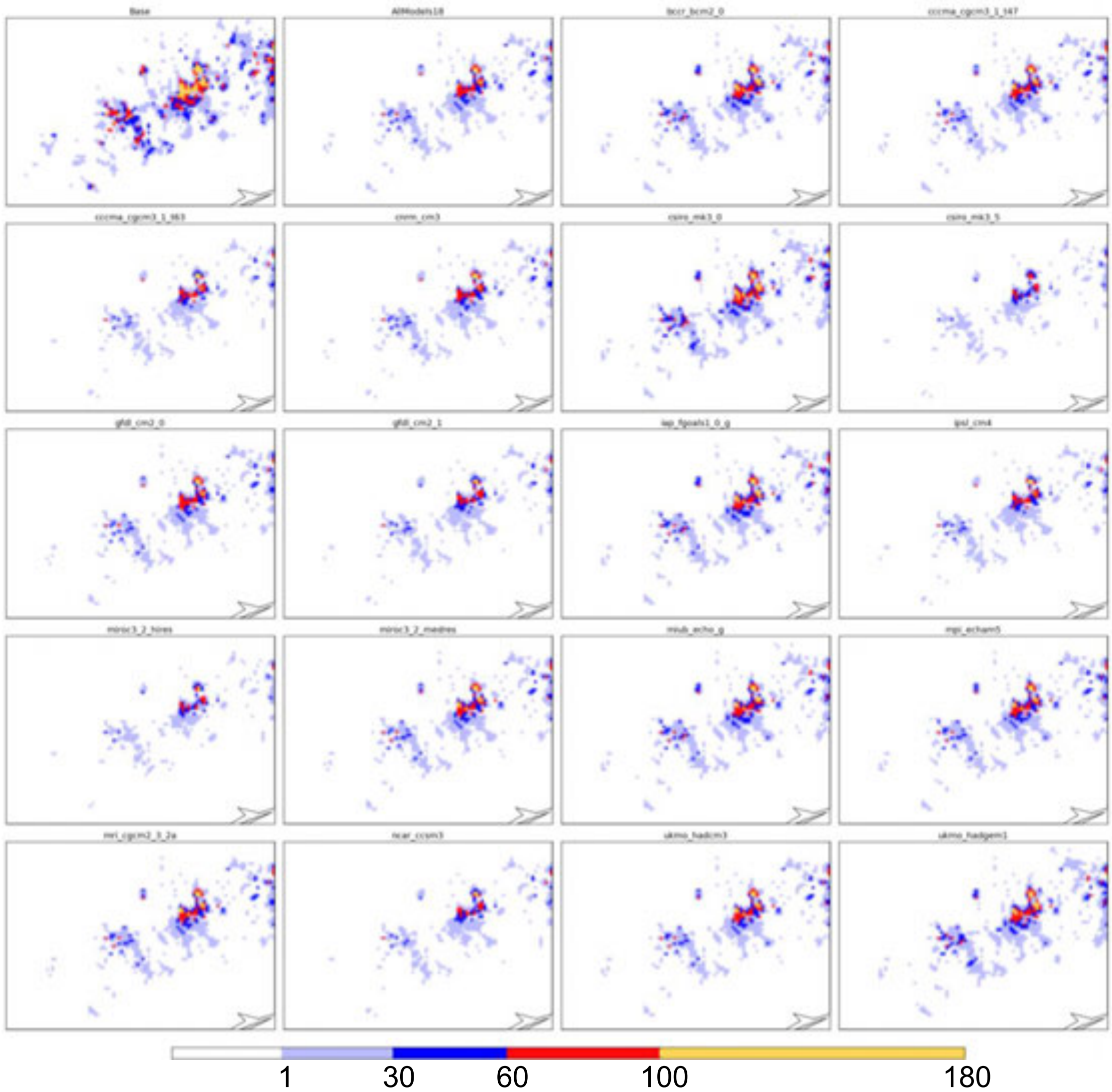


Figure 15: Average snow-cover duration (number of days with at least 1 cm of snow) over north-east Victoria for a 20-year period centred on 1990 (top-left) and a 20-year period centred on 2050 (medium-A1B emissions scenario) for 18 climate models. The 18-model average pattern is shown in the top row, next to the "base" case.

Table 5: Simulated percentage changes in the area of north-east Victoria with at least 1, 30 or 60 days annual-average snow-cover duration for 20-year periods centred on 2050 for three emissions scenarios: low (B1), medium (A1B) and high (A1FI). The range of changes represents the spread of results from 18 climate models. Simulated changes have been rounded to the nearest 5%.

Snow duration	2040-2059 low	2040-2059 medium	2040-2059 high
At least 1 day	-25% to -55%	-30% to -70%	-35% to -75%
At least 30 days	-35% to -75%	-50% to -85%	-55% to -90%
At least 60 days	-45% to -80%	-55% to -90%	-60% to -95%

Changes in average snow-season duration by 2020 have been estimated at four ski resorts (Table 6). For example, at Falls Creek, the average duration declines from 125 days in 1990 to 100-120 days for the low (B1) scenario, 95-115 days for the medium (A1B) scenario and 100-120 days for the high (A1FI) scenario. Across the four resorts, the snow season becomes 5-35 days shorter, largely independent of the scenario.

By 2050, the snow seasons become even shorter (Table 7). Across the four resorts, the snow season becomes 20-55 days shorter for the low (B1), 25-70 days shorter for the medium (A1B), and 30-85 days shorter for the high (A1FI) scenario.

Table 6: Simulated average duration (days) of at least 1 cm of snow-cover at four ski resorts for 20-year periods centred on 1990 and 2020, for three future emission scenarios: low (B1), medium (A1B) and high (A1FI). The range of days for 2020 represents the spread of results from 18 climate models.

Site	1980-1999	2010-2029 low	2010-2029 medium	2010-2029 high
Falls Creek	125	100-120	95-115	100-120
Mt Hotham	130	105-120	100-120	105-120
Mt Buller	110	80-100	75-100	80-100
Mt Buffalo	80	50-70	45-70	55-70

Table 7: Simulated average duration (days) of at least 1 cm of snow-cover at four ski resorts for 20-year periods centred on 1990 and 2050, for three future emission scenarios: low (B1), medium (A1B) and high (A1FI). The range of days for 2050 represents the spread of results from 18 climate models.

Site	1980-1999	2040-2059 low	2040-2059 medium	2040-2059 high
Falls Creek	125	75-105	55-100	45-95
Mt Hotham	130	80-110	60-105	50-100
Mt Buller	110	55-90	35-80	25-75
Mt Buffalo	80	25-60	15-50	10-45

4. DISCUSSION AND RESEARCH PRIORITIES

Analysis of observed trends in snow conditions at Rocky Valley Dam from 1954-2011 shows that the decline in maximum depth and earlier end to the snow season reported in previous studies (Hennessy *et al.*, 2003; Nicholls 2005) has continued. Recent observed changes in maximum snow depth have been compared with projected changes for the closest snow-model grid-cell with comparable altitude (Figure 16). To remove the bias between the observed and simulated snow depths, we use relative projections and scale these with the observed 1990 baseline. Furthermore, we include an estimation error of 20-year averages to allow for the influence of natural variability.

The observed changes in maximum snow depth since 1990 are consistent with changes projected from 1990 onwards due to increasing greenhouse gases. The most recent years are inconsistent with the projected changes according to the low emission scenario (B1). Given that emissions in recent years have been tracking between the medium (A1B) and high (A1FI) scenarios (Figure 7), it may be reasonable to expect the observed changes in maximum snow depth to follow projections for the medium-to-high emissions scenarios.

The observed trend towards an earlier end to the snow season was found to be strongly associated with increased average daily maximum temperatures in the Victorian Alps. Since this regional temperature increase is partly anthropogenic (Stott *et al.*, 2010), it seems likely that the observed trend towards an earlier end to the snow season would also be partly anthropogenic. However, until a more rigorous assessment of the causes of changes in snow properties is conducted, it is not possible to formally determine the degree to which changes in Victorian Alpine snow characteristics are linked to anthropogenic warming (for a review of formal detection and attribution studies see Stott *et al.,* 2010).

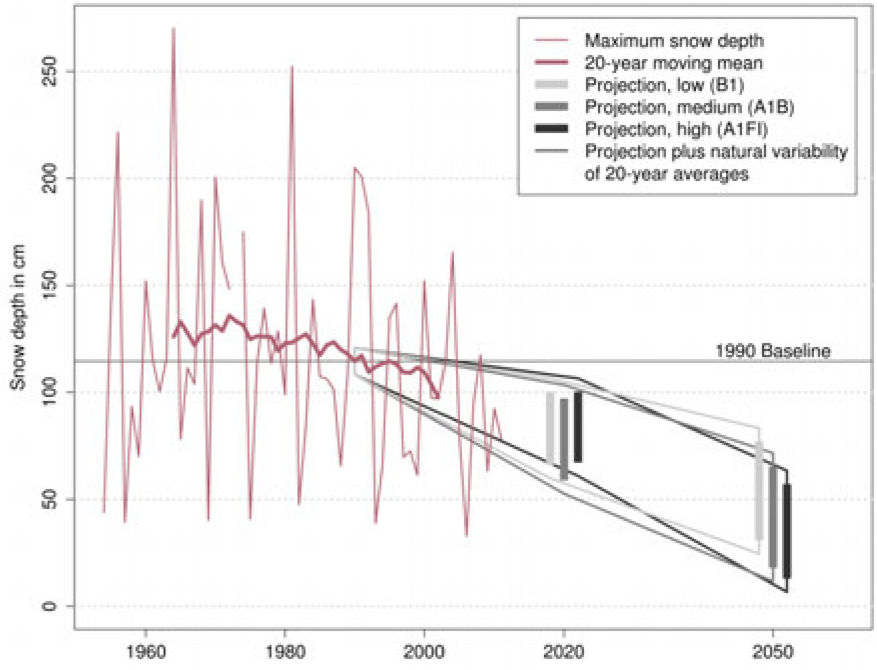


Figure 16: Observed maximum snow depth at Rocky Valley Dam from 1954-2011 (red line) and its 20-year moving average (thick red line) along with the range of projected changes according to three different emissions scenarios (grey bars) for 20-year periods centred on 2020 and 2050. The grey polygons denote the expected bounds for 20-year averages allowing for natural variability. Upper and lower bounds on the projections are linearly interpolated between 1990 and 2020 and between 2020 and 2050.

The updated projections confirm previous findings, with high confidence in a general decrease in snow depth and duration over the coming decades. While some of the updated projections appear to be smaller than the previous report, this is mainly due to differences in the averaging areas, i.e. the previous report included the NSW Alps.

There is significant uncertainty about the rate of decrease. The range of projections from 18 climate models is wide. Narrowing this range might be possible through improvements in climate models and / or improved methods for quantifying uncertainty. Simulations from a new suite of over 40 CMIP5 climate models are being generated during 2011 and 2012. Evaluation of the performance of these simulations over the Australian Alps is a high priority. The new models could be used in an updated assessment of the impact of climate change on snow cover.

The current version of the CSIRO snow model requires monthly temperature and precipitation data on a 2.5 km grid. However, the Bureau of Meteorology has produced daily temperature and rainfall data on a 5 km grid over Australia, from 1910-2010 (Jones *et al.*, 2009). The Australian National University has developed similar data, with enhanced modelling of daily precipitation occurrence and amount, on a 1 km grid from 1968-2010. If the CSIRO snow model was upgraded to accept gridded daily data, snow accumulation and ablation would be better simulated. There is also an opportunity to upgrade the snow-melt component of the CSIRO snow model using a module from New Zealand's SnowSim model (Hendrikx and Hreinsson, 2010). This would allow for seasonal variability, albedo (reflectivity of old vs. new snow) and the effect of rain on snow.

This report has focused on projections averaged over 20-year periods. More attention needs to be paid to daily, monthly and annual variability in snow conditions, rather than 20-year averages. This would provide insight into the frequency and timing of warm-wet days (rain on snow leading to faster snow-melt) and cold-dry days (good for snow-making), the frequency of good and bad starts to each snow-season, and the frequency of good and bad overall snow seasons.

At ski resorts, seasonal variability in snow conditions can be managed to some extent through a range of practices such as snow-making, snow-grooming and snow-farming. The scope for adaptation through snow-making should be revisited, allowing for recent and projected improvements in the technology. This would require hourly wet-bulb temperature data from ski resorts.

This report has focused on snow changes in Victoria. Future research should expand the region of interest to include other parts of the Australian Alps in New South Wales and Tasmania. A comparison with observed trends and projections in New Zealand would also be valuable.

5. CONCLUSIONS

Snow measurements at Rocky Valley Dam (altitude 1650 m) from 1954-2011 indicate a clear trend to lower maximum snow depths and an earlier end of the snow season. The variability in maximum snow depth can be well explained by maximum temperature and precipitation from June to August, with changes in temperature and precipitation contributing in roughly equal parts. The earlier end of the snow season is clearly dependent on changes in temperature.

Temperature and precipitation projections from 18 climate models, driven by different greenhouse gas emission scenarios, are used as input to the CSIRO snow model. These simulations indicate that the end of the snow season is likely to occur earlier in future, with a slightly later start, and lower maximum depths. The average snow-covered area of north-east Victoria is likely to decline. These trends will be superimposed on large natural year-to-year variability. The number of good snow seasons is expected to decline while the number of poor seasons is likely to increase.

ACKNOWLEDGEMENTS

This research was supported by the Victorian Department of Sustainability and Environment.

We acknowledge the modelling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, US Government Department of Energy.

The State Electricity Commission of Victoria and AGL Hydro kindly provided snow depth measurements at Rocky Valley Dam.

We also thank David Kent (CSIRO) for computer programming assistance.

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APPENDIX 1: MAXIMUM SNOW DEPTHS FOR 2050 B1 AND A1FI

2050 B1

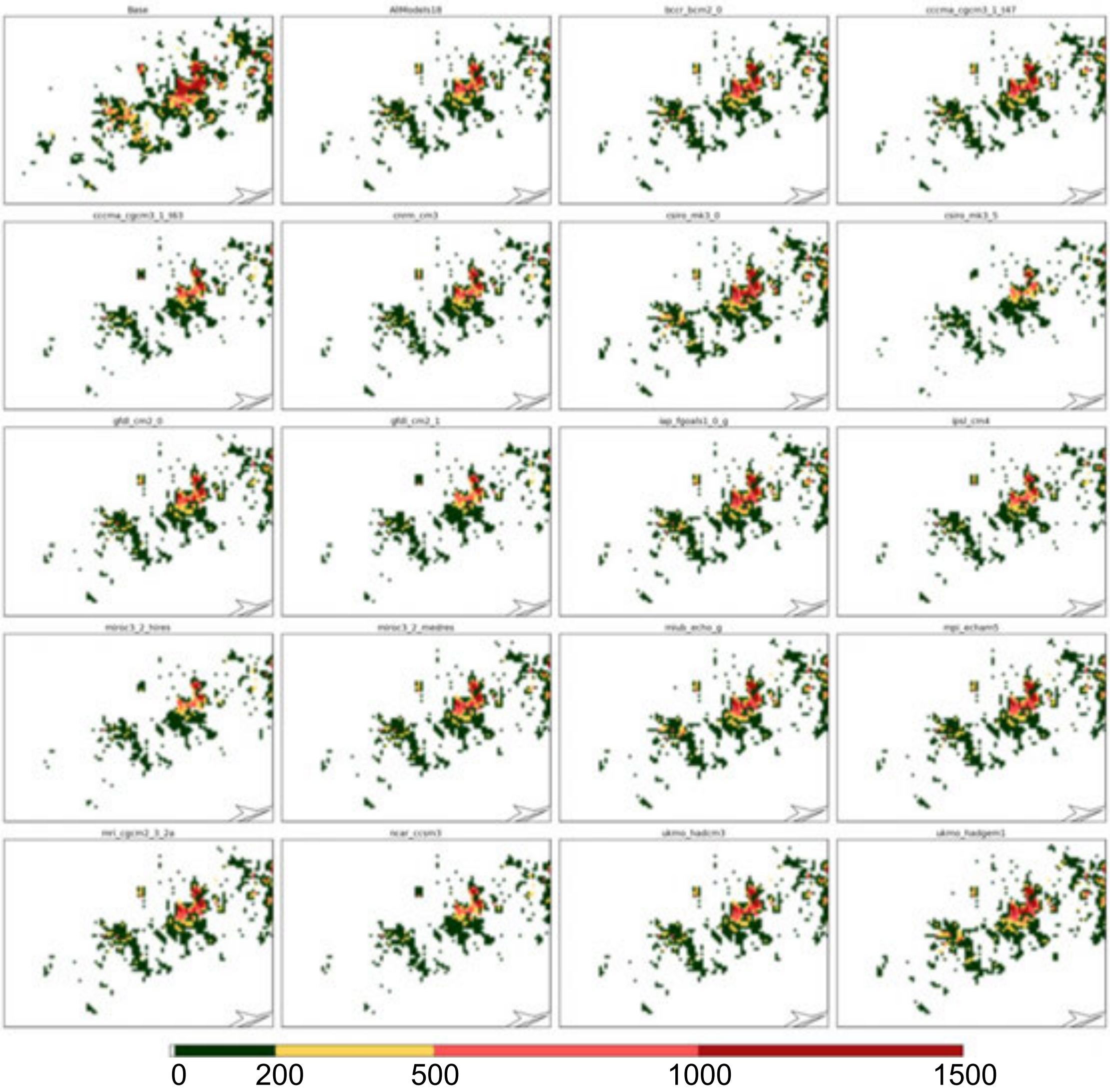


Figure A1: Average maximum snow-depth (mm) over north-east Victoria for 20-year periods centred on 1990 (top-left) and 2050 (low-B1 emissions scenario) for 18 climate models. The 18-model average pattern is shown in the top row, next to the "base" case.

2050 A1FI

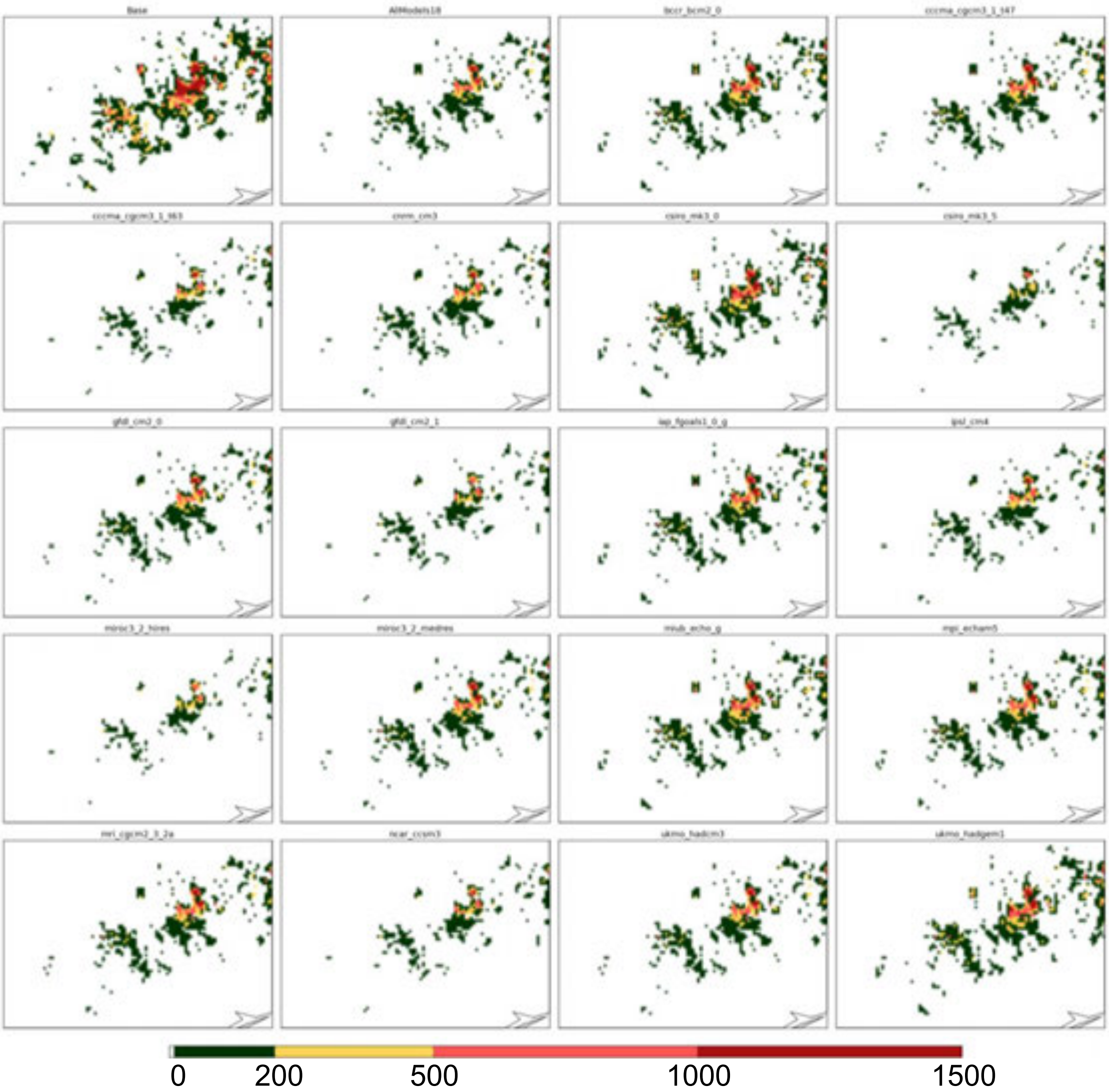
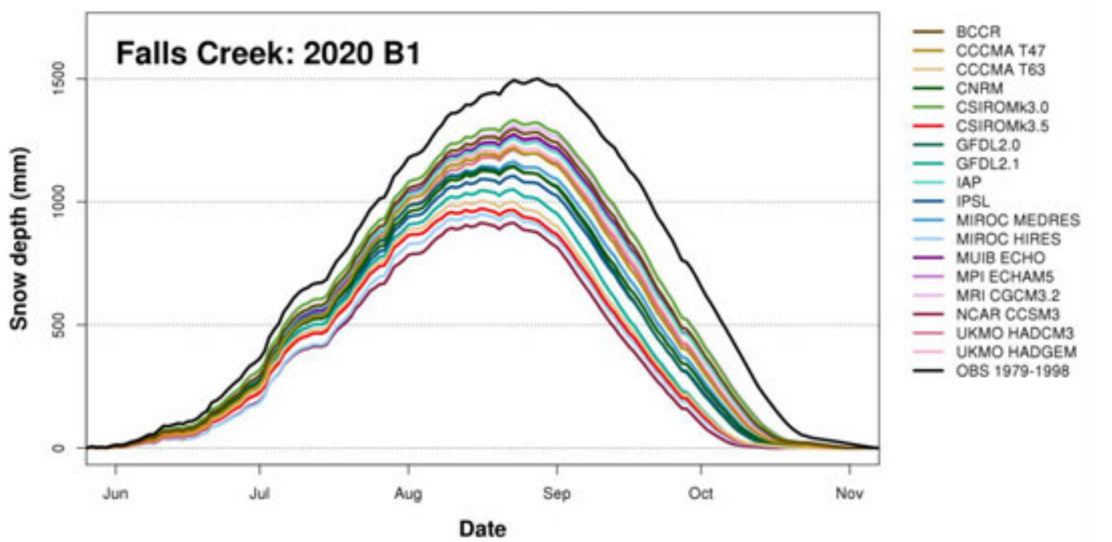


Figure A2: Average maximum snow-depth (mm) over north-east Victoria for 20-year periods centred on 1990 (top-left) and 2050 (high-A1FI emissions scenario) for 18 climate models. The 18-model average pattern is shown in the top row, next to the "base" case.

APPENDIX 2: SNOW PROFILES FOR 2020 AND 2050 B1 AND A1FI



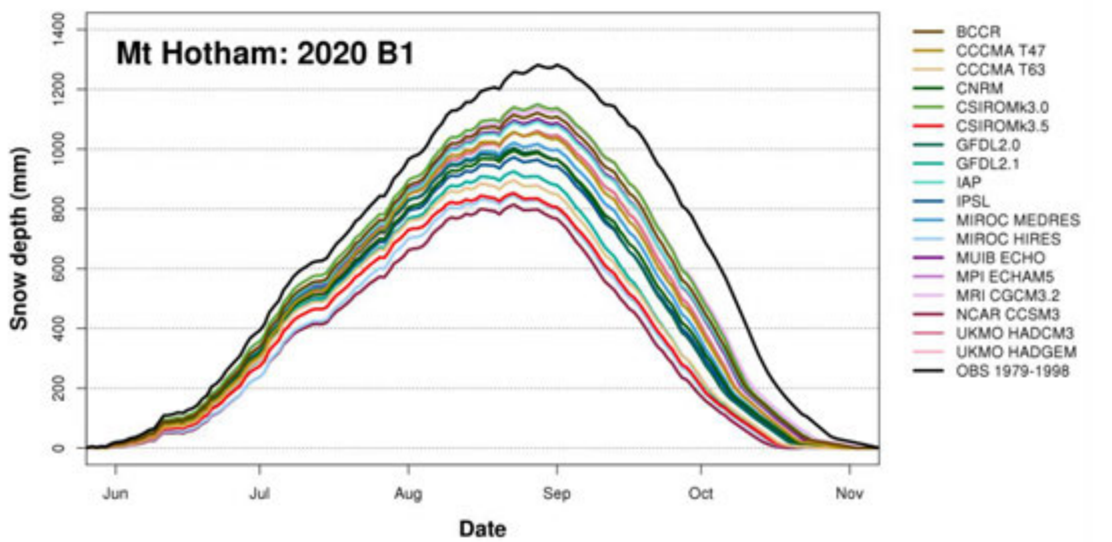
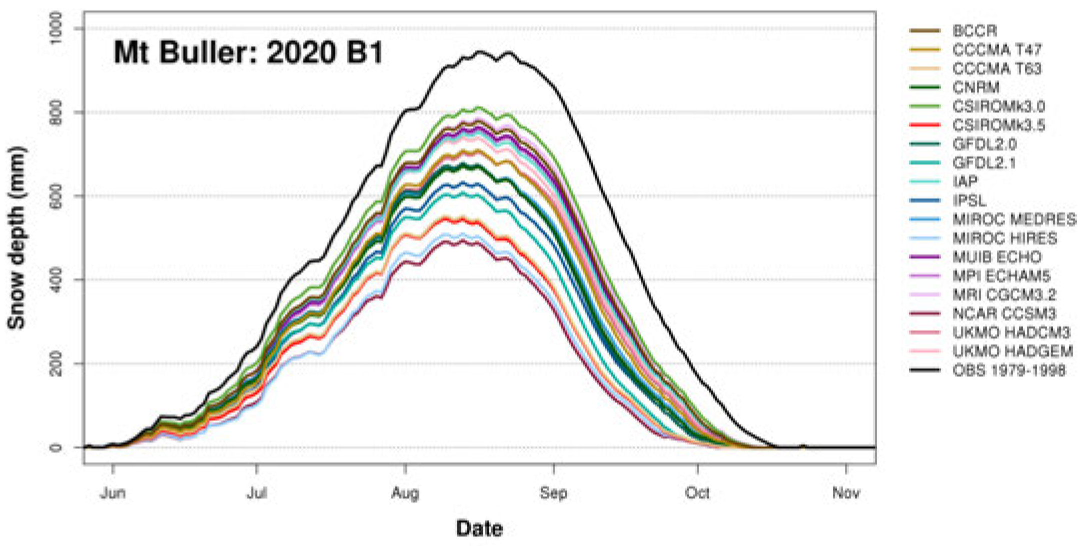


Figure A3: Simulated snow depth profiles for 20-year periods centred on 1990 (black line) and 2020 (coloured lines) for 18 climate models and the low-B1 emissions scenario at Falls Creek and Mt Hotham.



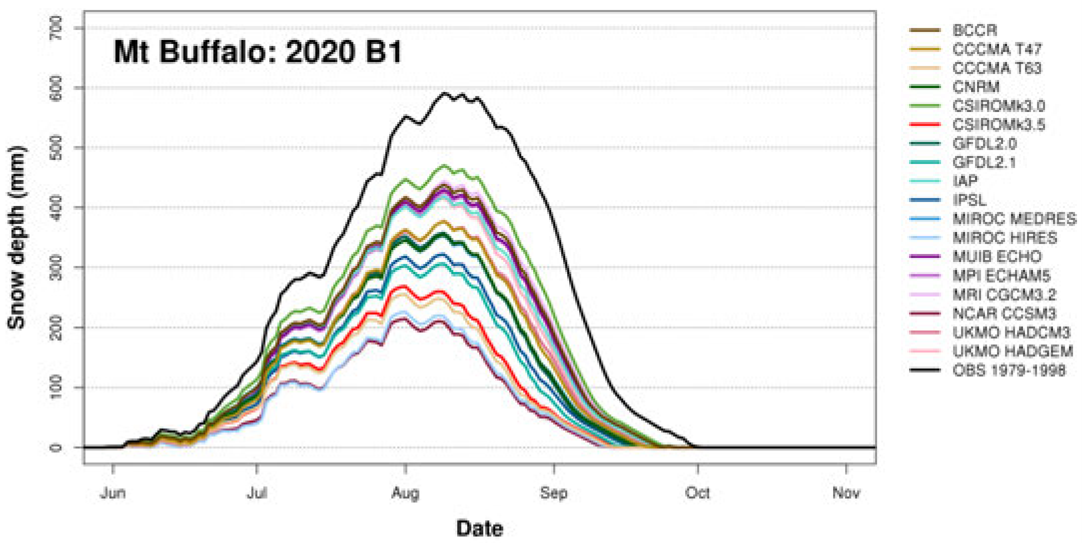
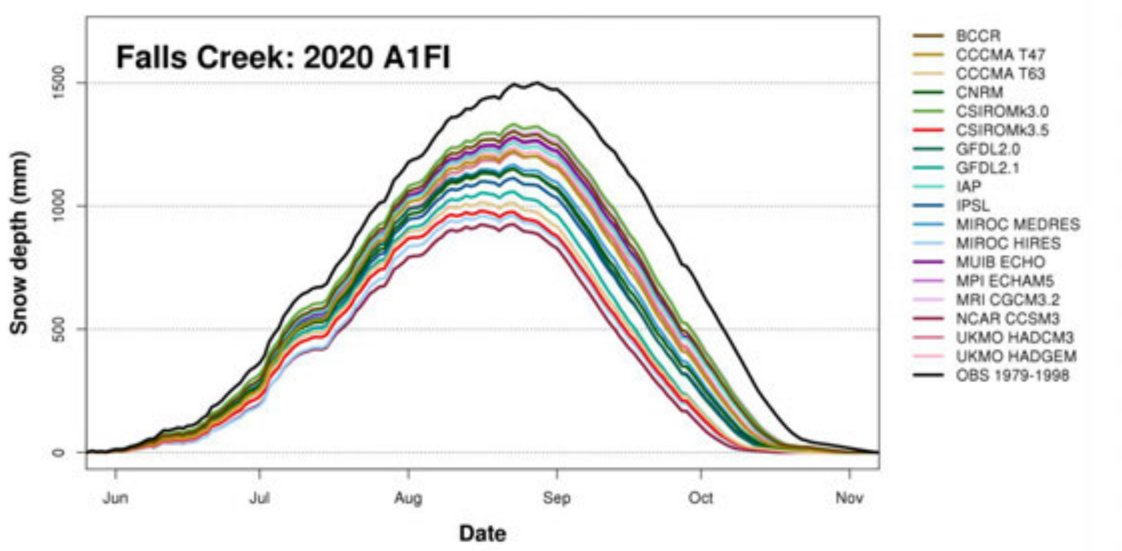


Figure A4: Simulated snow depth profiles for 20-year periods centred on 1990 (black line) and 2020 (coloured lines) for 18 climate models and the low-B1 emissions scenario at Mt Buller and Mt Buffalo.



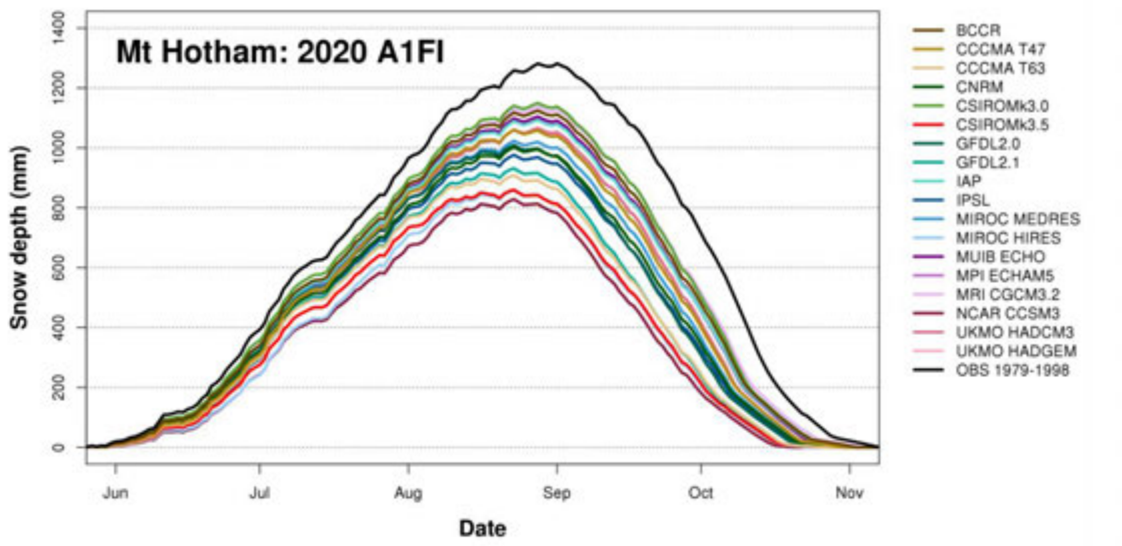
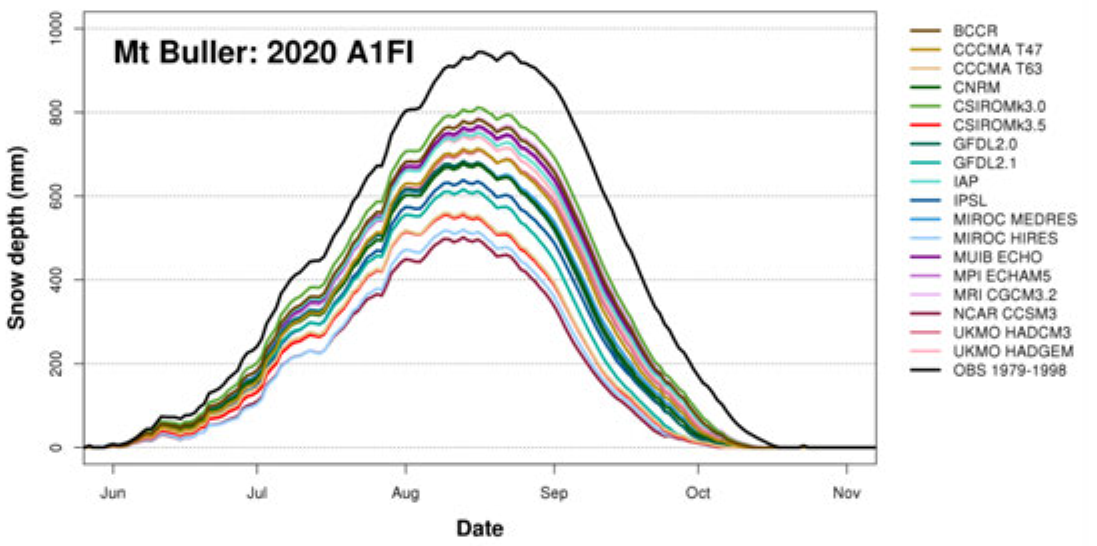


Figure A5: Simulated snow depth profiles for 20-year periods centred on 1990 (black line) and 2020 (coloured lines) for 18 climate models and the high-A1FI emissions scenario at Falls Creek and Mt Hotham.



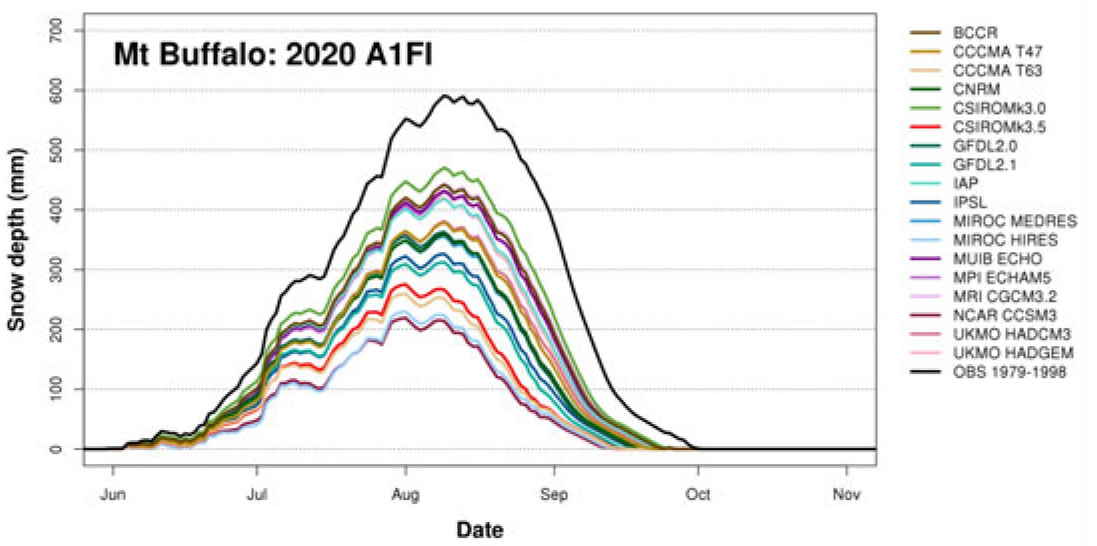
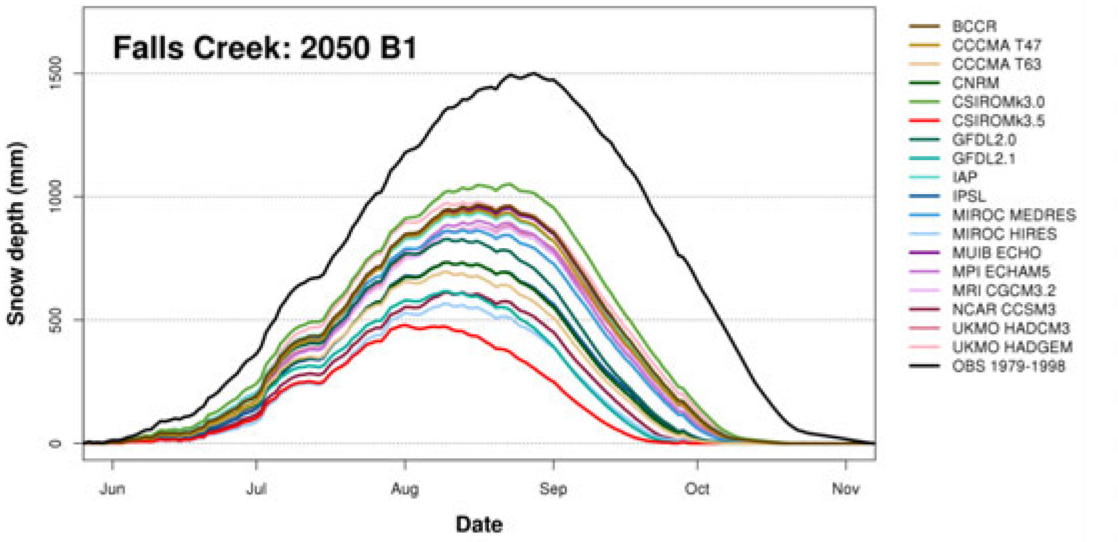


Figure A6: Simulated snow depth profiles for 20-year periods centred on 1990 (black line) and 2020 (coloured lines) for 18 climate models and the high-A1FI emissions scenario at Mt Buller and Mt Buffalo.



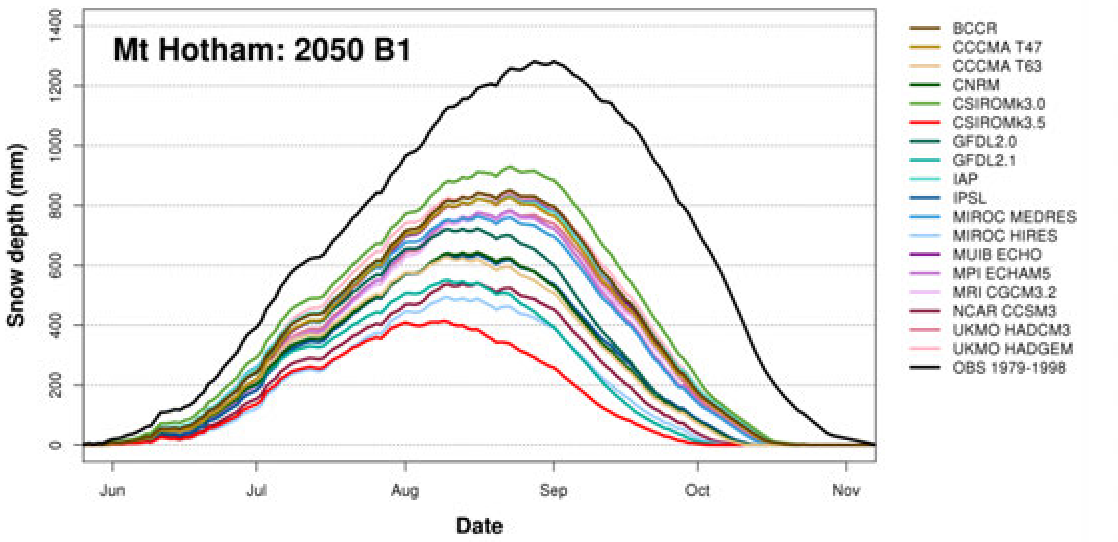


Figure A7: Simulated snow depth profiles for 20-year periods centred on 1990 (black line) and 2050 (coloured lines) for 18 climate models and the low-B1 emissions scenario at Falls Creek and Mt Hotham.

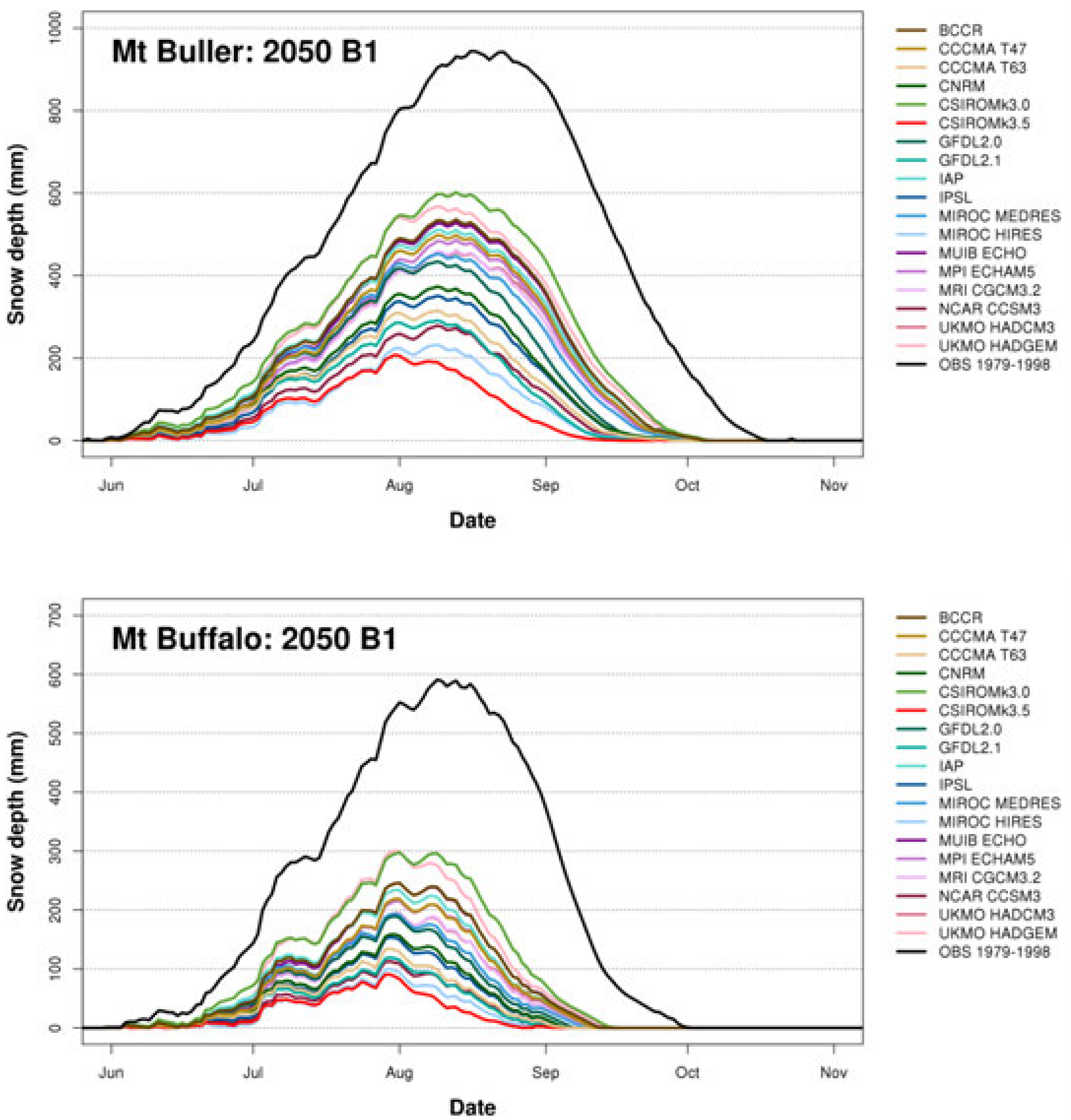
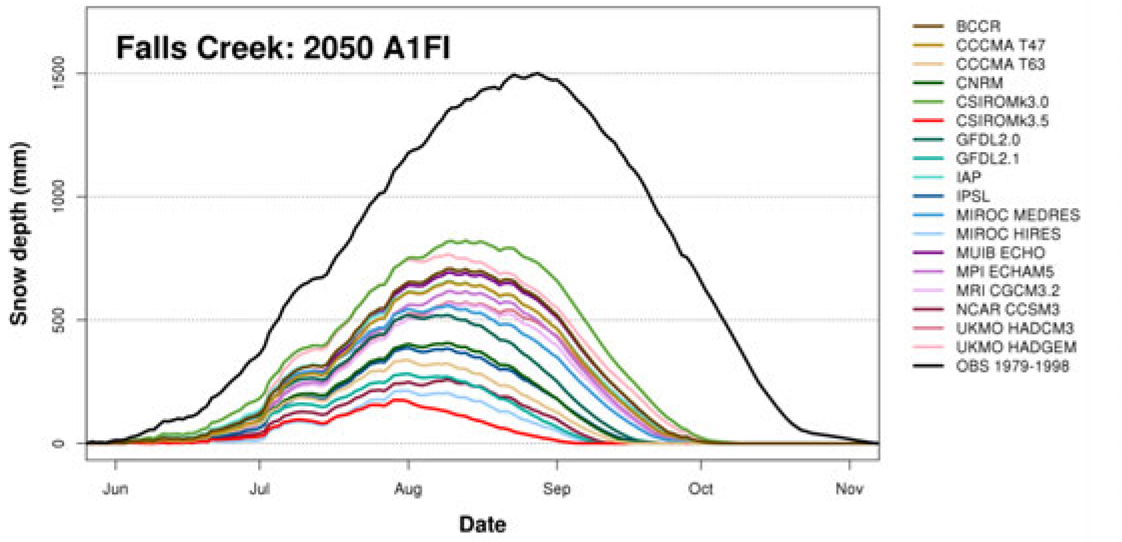


Figure A8: Simulated snow depth profiles for 20-year periods centred on 1990 (black line) and 2050 (coloured lines) for 18 climate models and the low-B1 emissions scenario at Mt Buller and Mt Buffalo.



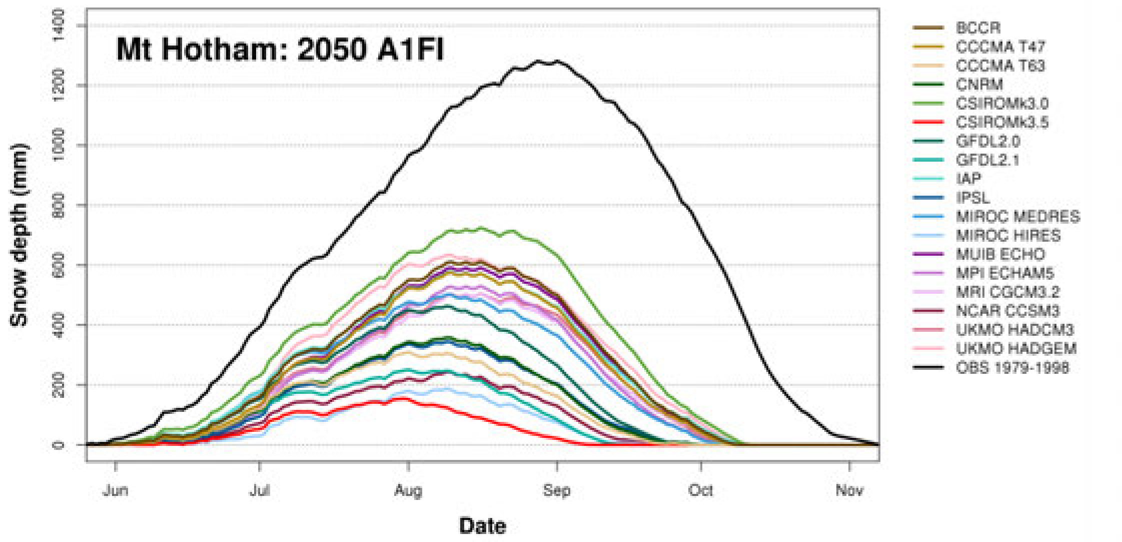
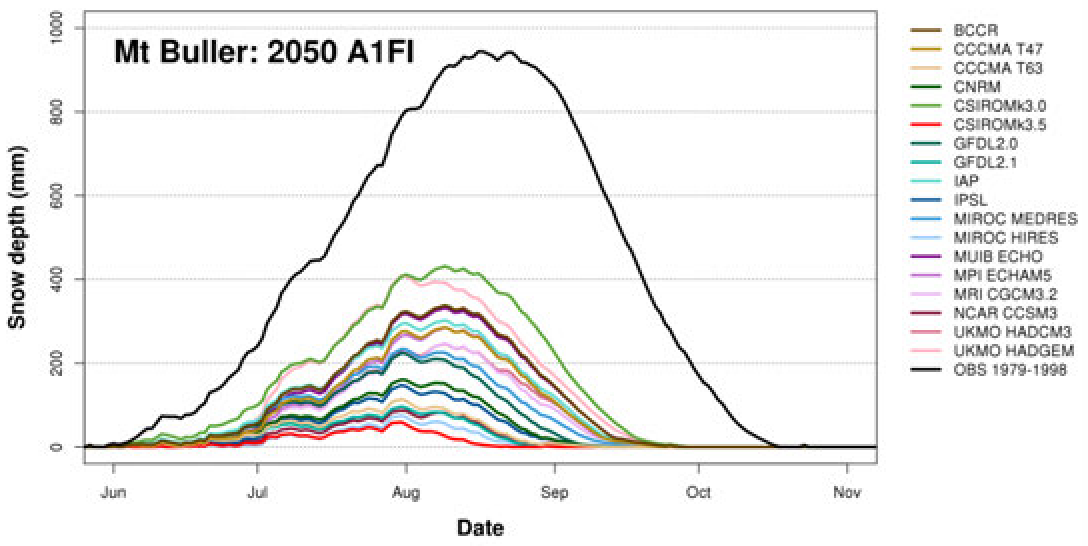


Figure A9: Simulated snow depth profiles for 20-year periods centred on 1990 (black line) and 2050 (coloured lines) for 18 climate models and the high-A1FI emissions scenario at Falls Creek and Mt Hotham.



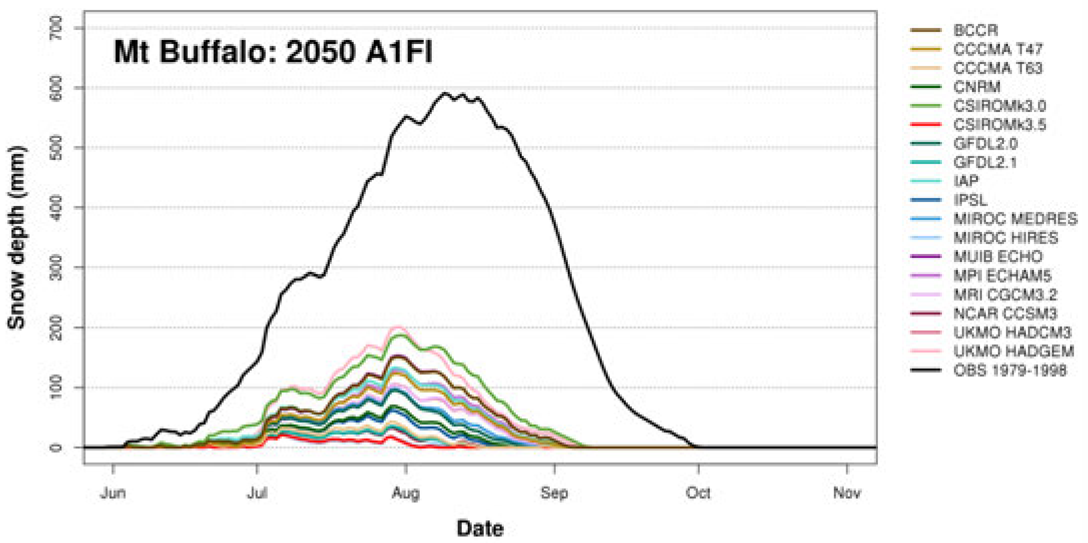


Figure A10: Simulated snow depth profiles for 20-year periods centred on 1990 (black line) and 2050 (coloured lines) for 18 climate models and the high-A1FI emissions scenario at Mt Buller and Mt Buffalo.

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