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A new perspective on Australian snow

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Abstract

The Australian Alps have a unique climatological, ecological and hydrological environment and play a key role in water supply for southeastern Australia. Using resort observations we compile a new and robust snow accumulation data set. Both maximum snow depth and total snow accumulation have declined over the last 25 years. A significant decreasing trend was observed for the total number of light snow days, whereas the total number of heavy snow occurrences has remained constant. Maximum temperatures are highly related to all snow variables. It is suggested that global warming is already impacting light snowfall events, while heavy events are less affected.

Keywords: **snowfall; Australia; climate; trends**

1. Introduction

The Australian Alps, running down the east coast of Australia, are an important source of freshwater and home to a multi-million dollar ski industry. Snowfall in the region, whilst already in a fragile state, is highly susceptible to precipitation and temperature regimes, and is currently experiencing declines due to changes in these parameters.

Duss (1992), using the Snowy Hydro Limited (SHL) data set for Spencers Creek, southwest of Canberra, created an integrated snow profile (by integrating snow depth over time) in which he found no declining trend from 1910 to 1991. It was shown by Whetton *et al.* (1996) that the variation of snow cover is related to the prevailing precipitation and temperature anomalies. For many years the most basic snow models were based on a monthly data set of these two parameters alone (Galloway, 1988; Duss, 1992; Whetton *et al.,* 1996; Hennessy *et al.,* 2003).

In a 2003 report, Hennessy *et al.* (2008) discussed findings that temperatures were increasing at a greater rate in the higher altitudes of southeastern Australia than that of lower altitudes, whilst rainfall in the Victorian Alps had experienced a small decrease. A weak decline in the maximum snow depth was observed across several sites over the 1957 to 2002 period. Hennessy *et al.* (2008) also noted a decline in late season (August and September) maximum snow depths.

Nicholls (2005), in a comprehensive analysis of the snow depth records at Spencers Creek, showed that whilst there was a slight decline in the maximum snow depth since 1962 (10%), the weak decline in wintertime precipitation was not strong enough to explain this trend, whereas the increase of wintertime temperature experienced was too strong. Analysis of the springtime snow depths showed a much stronger decline of up to 40% over the same period (1962–2002), which the author attributed largely to the increase of temperature.

In 2009, Nicholls updated this work across the period 1954 to 2008, to confirm a continuing, albeit insignificant, decline of maximum snow depths and a strong, significant decline in spring time snow depths.

Bhend *et al.,* 2012, using snow depth data from the Rocky Valley Damn site, found that maximum snow depths have declined over the 1954–2011 period, with the majority of this occurring in the recent past. Furthermore, they indicated that snow seasons are ending earlier.

Davis (2013) found at Spencers Creek, snow depths have decreased by about 15% in the last decade. By using a statistical linear regression of temperature and precipitation data, it was estimated that snow depths in the beginning of the 20th century were 5–14% greater than the 1961–1990 average.

When considering the future, the simulation of snowfall has received considerably less attention than the simulation of rainfall in southeastern Australia or snowfall elsewhere in the world. The snow cover model first developed by Galloway (1988), and updated by Whetton *et al.* (1996), has been the most predominantly used for the region. This model uses monthly precipitation and temperature, the daily temperature standard deviation and an empirically derived relationship specific to the Australian Alps to estimate snowfall and ablation (melt). By using a high-resolution temperature and precipitation grid, Whetton *et al.* (1996) (and hence Hennessy *et al.,* 2003, 2008; Bhend *et al.,* 2012) were able to model snow cover and duration. The most recent work by Bhend *et al.* (2012), focusing on the 2020 and 2050 periods, indicates that the current decline in maximum snow depth is likely to continue. Shorter seasons are projected, mainly owing to earlier spring melt, with later season onset also contributing, while the area of snow cover across the Victorian Alps is likely to decline.

In this study, a new daily snowfall accumulation data set is presented for the first time, which is more closely related to rainfall and temperature variations than the

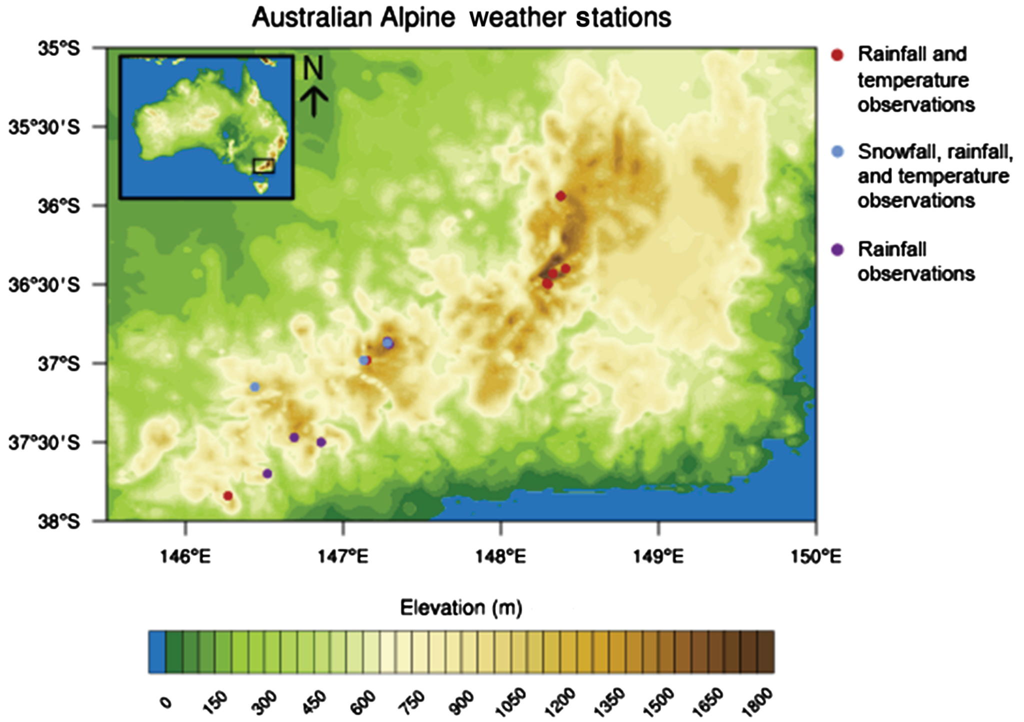

Figure 1. Topographical map of the Australian Alps with the locations of weather stations marked in red for rainfall and temperature observations, blue for rainfall, temperature and snowfall observations and purple for rainfall observations only.

maximum snow depth traditionally used. This data is explored in terms of trends and variability and its relationships to climate drivers known to influence rainfall in the southeast Australian region. Also for the first time we are able to explore the frequency of certain snowfall events. Finally, using projections from the Climate Model Intercomparison Project 3 (CMIP3), the future of snowfall events greater than 20 cm in southeastern Australia is explored.

2. Data and methods

2.1. Data selection

Data used in this study consists of temperature and precipitation received from the Bureau of Meteorology (BOM). Weather stations must be above 1400 m (with Thredbo Village the exception) in altitude and within the box 35–38°S and 145.5–150°E (Figure 1 and Table 1). The time period of interest is from 1988 to 2013, chosen due to the limitation of the snowfall data, during the June, July, August, September (JJAS) season. New South Wales weather station data is included in this analysis as Victorian data alone does not cover the entire time period satisfactorily. All weather station data underwent quality control (performed by the authors), which is detailed below.

Snow depth observations were obtained from the Mount Hotham Resort Management, Mount Buller and Mount Stirling Resort Management/Mount Buller Ski Lift PTY LTD, Falls Creek Resort Management Board/Falls Creek Ski Lift Company, each located in the Victoria Alps, and the Alpine Resorts Coordinating Council (ARCC). The data received begins in 1988 for Mount Buller and Mount Hotham and 1993 for Falls Creek. It is an average of three sites across the mountain, in an area unaffected by snowmaking, wind barriers and shade. The locations and elevations of the nine sites are provided in Table 1.

The European Centre for Medium-range Weather Forecasting's (ECMWF) ERA-Interim data is used as an estimate of the average daily 850 hPa temperature (T850) during heavy snowfall events. By averaging the T850 over the box of interest defined above, such an estimate can be made. The ERA-Interim data has a resolution of $0.75° \times 0.75°$ and was obtained from the ECMWF Data Server (Dee *et al.,* 2011).

Climate drivers analysed in this study include the Southern Annular Mode (SAM), defined as the leading empirical orthogonal function of monthly mean 700 hPa height anomalies north of 20°S (Gong and Wang, 1999), and obtained from the National Oceanic and Atmospheric Administration's Climate Prediction Centre. The Southern Oscillation Index (SOI) was used as a proxy of the El Niño Southern Oscillation (ENSO) and was obtained from the BOM. SOI is defined as the standardized pressure difference between Tahiti and Darwin (Troup, 1965). The Indian Ocean Dipole (IOD) was explored via the Dipole Mode Index (DMI), defined as the difference between sea surface temperatures (SSTs) over the west Indian Ocean (10°S–10°N, 50–70°N) and the southeastern Indian Ocean (10°S–0°, 90–110°E) (Saji *et al.,* 1999). This data set was obtained from the Japanese Agency for Marine-Earth Science and Technology database. Lastly,

Table 1. Latitude, longitude, elevation and time span of snow plots and weather stations used for this study.

Name	Latitude	Longitude	Elevation	Time period
	Snow depth plots			
Falls Creek 1	36.86	147.26	1639 m	1993–2013
Falls Creek 2	−36.86	147.26	1638 m	1993–2013
Falls Creek 3	−36.87	147.27	1675 m	1993–2013
Mount Hotham 1	−36.99	147.145	1760	1988–2013
Mount Hotham 2	−36.99	147.15	1755	1988–2013
Mount Hotham 3	−36.98	147.14	1675	1988–2013
Mount Buller 1	−37.14	146.44	1708	1988–2013
Mount Buller 2	−37.15	146.43	1731	1988–2013
Mount Buller 3	−37.15	146.43	1689	1988–2013
	Weather stations			
Charlotte Pass[a]	−36.43	148.33	1755	1930–2013
Thredbo AWS[a]	−36.49	148.29	1957	1966–2013
Thredbo Village[a]	−36.50	148.30	1380	1969–2013
Perisher Valley Ski Centre[a]	−36.40	148.41	1735	1976–2010
Cabrumurra SMHEA	−35.94	148.38	1475	1955–1999
Cabrumurra SHMEA AWS[a]	−35.94	148.38	1482	1996–2013
Mt Buller[a]	−37.15	146.44	1707	1948–2013
Falls Creek SEC	−36.86	147.28	1510	1947–1990
Falls Creek Rocky Valley	−36.88	147.29	1661	1951–2013
Mount Hotham[a]	−36.98	147.15	1750	1977–1990
Falls Creek[a]	−36.87	147.28	1765	1990–2013
Mount Hotham[a]	−36.98	147.13	1849	1990–2013
Mount Useful	−37.70	146.52	1440	2002–2013
Mount Tamboritha	−37.47	146.69	1446	1989–2013
Mount Baw Baw[a]	−37.84	146.27	1561	1991–2013
Mount Wellington	−37.50	146.86	1559	1997–2013

[a]Weather stations that provide rainfall and temperature data, and whether stations with no indicators denote just rainfall data. Note that the time span does not necessarily indicated data was available or suitable for this research during the entire period.

the subtropical ridge (STR) position and intensity, as defined by the Drosdowsky (2005), index is explored. This data was obtained from the BOM. This index measures the local maxima of monthly mean surface pressure for the area of 10–44°S and 145–150°E. The mean surface pressure is derived from station data that has been interpolated over a 1° grid.

2.2. Quality control

Only one station (Cabramurra SMHEA for temperature) was available in the BOM's high quality data set that fitted the above criteria. For this reason the raw station data was used and put through the following quality tests. Having removed null values, quality control of the observational data was undertaken following the method of Chubb *et al.* (2011) in order to determine how well the stations related to one another. This was performed by creating a daily average of the rainfall, temperature and snowfall data sets, then correlating each individual station back to this daily average. If the correlation was below 0.65 for rainfall or temperature stations that had undergone quality control by the BOM, then the station was not used. For temperature, snowfall and rainfall stations that had not undergone quality control by the BOM the correlation was required to be greater than 0.75. Furthermore, the BOM data had to span 10 years with at least 8 years having more than 80% of daily data available. This quality control method was also used in the Fiddes *et al.*'s (2014) work. All correlations in this work were performed using the Pearson correlation method (Wilks, 1995).

2.3. The total snow accumulation data set

Unlike the majority of snow data used in previous literature, we now have daily snow depth measurements allowing us, for the first time, to estimate the amount of snow that had either fallen or melted each day. This is done simply by subtracting one day from the next in order to find the change in depth. Subsequently, by summing up only days when this change is positive (indicating snowfall) for the entire JJAS season and ignoring any negative changes (snowmelt), we developed a data set similar to that of the total JJAS rainfall data set. We have named this new data set the snow accumulation data set. This data set is less susceptible to changes within the snowpack (compression).

2.4. Future climates

Future climate projections were selected using the CSIRO's Representative Future Climate framework; a simplified model selection process using the CMIP3 array, whereby models that represent a range of future climatic scenarios based on parameters of interest are analysed as opposed to analysing the full complement of CMIP3 models (Whetton *et al.,* 2012). In this work, changes in precipitation and temperature were considered important; significant warming and a reduction in precipitation are considered to be detrimental to the occurrence of snowfall, whereas little change in these parameters is considered to be a 'best' case scenario.

The models that most closely represent these scenarios were the CSIRO Mk3.5 model, representing a *hotter, drier climate* and the Japanese Model for Interdisciplinary Research on Climate (MIROC) Medres model, representing a *warmer climate, with little change in precipitation.* These selection processes were conducted by the authors and the CSIRO together.

The MIROC Medres model has 43 vertical levels and a horizontal grid of 1.4° longitude by 0.5°–1.4° latitude. The CSIRO Mk3.5 model has 18 vertical levels and a horizontal grid of 1.875° x 1.875° (CSIRO, 2013). The emission scenarios A1B, A1FI and B1 were chosen; for information on these see the work done by Nakicenovic *et al.* (2000). The years 2030, 2050 and 2070 are focused on in this study.

3. Results

3.1. Trends and variability

Table 2 displays the detrended correlations of snowfall variables with rainfall and temperature in the region, and key climate drivers. It can be observed that the

Table 2. Correlations of snowfall parameters total JJAS snow accumulation, maximum snow depth and number of days of snowfall with total rainfall, number of days of rain, the maximum observed temperature and the climate drivers: SOI, SAM, DMI, STR position and STR intensity.

	Total snow accumulation	Maximum snow depth	Number of snowfall days >1 cm	Number of snowfall days 1–10 cm	Number of snowfall days 11-20 cm	Number of snowfall days >20 cm
		Rainfall parameters				
Total JJAS rainfall	**0.59**	**0.54**	0.29	0.12	0.37	**0.60**
Number of rainfall days	**0.73**	**0.66**	**0.62**	**0.45**	**0.62**	**0.65**
		Temperature parameters				
Observed minimum temperature (°C)	−0.27	−0.34	**−0.54**	−0.59	−0.20	−0.10
Observed maximum temperature (°C)	**−0.64**	**−0.65**	**−0.85**	**−0.82**	**−0.49**	**−0.42**
		Climate drivers				
SOI	0.07	0.13	−0.03	−0.06	0.04	0.09
SAM	−0.11	−0.12	−0.17	−0.16	−0.20	0.07
DMI	−0.29	−0.22	−0.31	−0.28	−0.21	−0.20
STR position	−0.17	−0.26	−0.15	−0.08	−0.34	−0.02
STR intensity	−0.14	−0.12	−0.15	−0.07	−0.35	−0.04

Bold indicates significance to the 95th percentile.

total snow accumulation is more highly correlated with the rainfall variables than the maximum snow depth, indicating that it is a powerful measure of snowfall. Both snow accumulation and maximum snow depth show a strong relationship with maximum temperature, as do all the snow frequency variables. No significant correlations were apparent with snowfall variables and relevant climate drivers using the detrended data.

Figure 2 plots the average total snow accumulation and maximum snow depth from 1988 to 2013, as a percentage of their respective averages. The average maximum snow depth is 151 cm per season whilst the average total snow accumulation for this period is 234 cm. Declining trends of 23 cm per decade or 15% per decade with respect to the average are apparent for the maximum snow depth, in strong agreement with the work by Davis (2013). For snow accumulation, a 21 cm per decade (9%) decline is shown. Both of these trends reflect large changes in snowfall in the recent decades.

Figure 3 plots the total number of snowfall days (greater than 0 cm), the number of days between 1 and 10 cm, 11 and 20 cm and those above 20 cm experienced per JJAS season. The average number of snow days experienced per season for each of these parameters is 31, 24, 5 and 2 respectively. Interestingly, a strong decline in the frequency of snowfalls greater than 1 cm and of between 1 and 10 cm per JJAS season of approximately 5 days per 10 years (significant to the 95th percentile) exists for both. No trends are apparent in the number of snowfall events of 11–20 cm and greater than 20 cm.

The strong declines in the 1–10 cm group suggest that the decline in snow accumulation and depth is largely attributed to the loss of small scale snowfall events. In effect, these more marginal events are already being impacted to a greater extent by global warming than the larger snow events which occur during strong cutoff lows or embedded lows (troughs) (Fiddes *et al.*, 2014), which also tend to bring cold temperatures to the region.

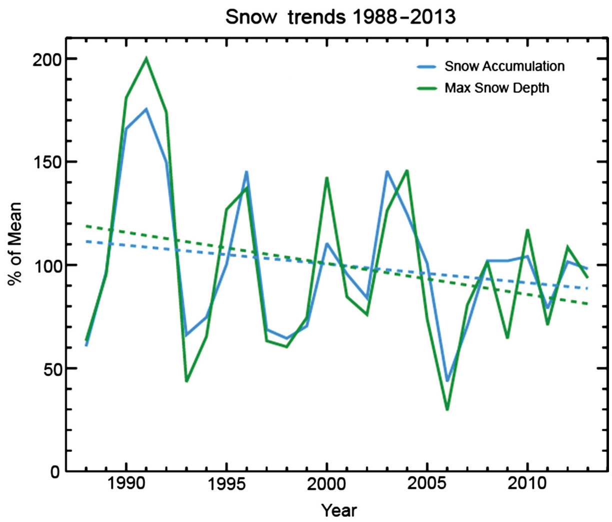

Figure 2. Time series (solid lines) of the snow accumulation (blue) and maximum snow depth (green) as a percentage of their respective averages over 1988–2013. The trends (in dotted lines), while not significant to the 95th percentile, show decreases of 9 and 15% respectively.

Correlations of events greater than 0 cm and events greater than 20 cm to snow accumulation yields $R = 0.80$ and $R = 0.84$ respectively. Analysis of the percentage of snow accumulation that each group makes up per season indicates that the 1–10 cm, 11–20 cm and greater than 20 cm groups make up 40.2, 34.6 and 23.5 percent on average (not shown). These percentages experience high interannual variability and have insignificant trends (of differing signs).

3.2. Future snowfall

Currently, global climate models are showing a poor ability to simulate regional precipitation, especially in southeastern Australia (Irving *et al.*, 2012). Using the MIROC Medres model as the best-case scenario and the

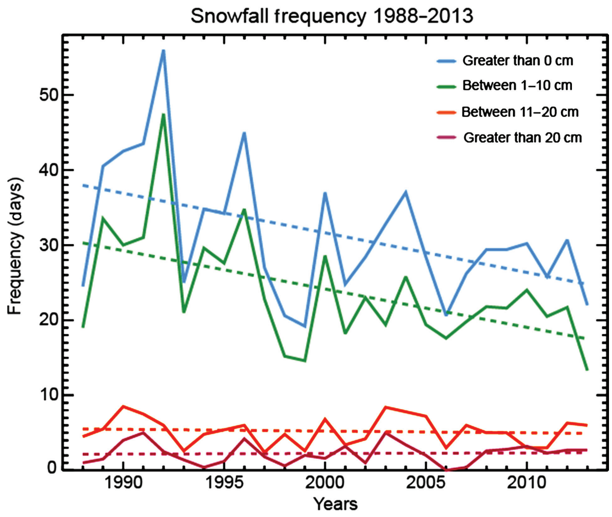

Figure 3. Time series of the total number of snowfall days (solid lines) for all events (greater than 0 cm) (blue), events between 1 and 10 cm (green), events between 11 and 20 cm (orange) and events greater than 20 cm (maroon) experienced per JJAS season. Trends are shown in dotted lines; both the number of events greater than 0 cm and between 1 and 10 cm are significant to the 95th percentile.

Table 3. The current average T850 estimated from ERA-Interim reanalysis over the box 145.5–150°E and 35-38°S, and the average T850 projected by the CMIP3 climate models for the years 2030, 2050, 2070 and emission scenarios A1B, A1FI and B1 over the same box.

	Current		
Reanalysis T850			2.88
	CSIRO Mk3.5 projections		
	A1B	A1FI	B1
2030	3.45	3.41	3.24
2050	4.10	4.41	3.62
2070	4.82	5.67	4.05
	MIROC Medres projections		
	A1B	A1FI	B1
2030	2.50	2.47	2.31
2050	2.92	3.17	2.54
2070	3.56	4.27	2.93

Temperatures are in degree Celsius.

CSIRO Mk3.5 model as the worst, we compare the projected temperatures to those of today in order to determine how changes in temperature alone are likely to affect heavy snowfalls in the Australian Alps. Projected average changes in 850 hPa temperature (T850) over the region bounded by 145.5–150°E and 35–38°S are provided in Table 3, along with the average reanalysis T850 over the same region.

Figure 4 plots the histogram of reanalysis daily average T850 for heavy snowfall days. It is important to note that already, the distribution of T850 of heavy snowfall lies over the 0 °C boundary, with the mean at 0.96 °C and a standard deviation at 1.59 °C. This implies that just a small warming can have a dramatic effect

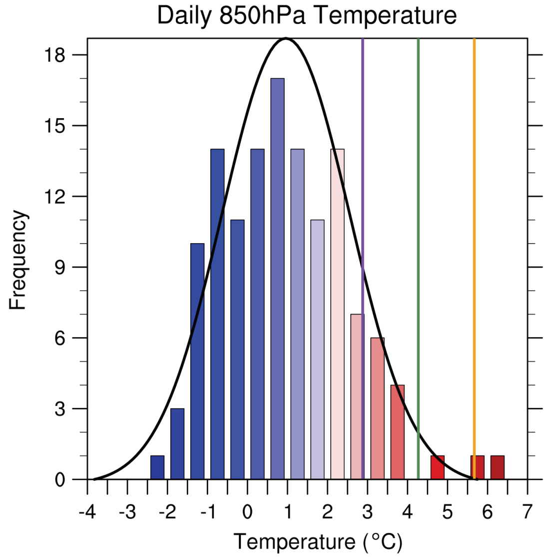

Figure 4. Histograms of the average T850 over the Alpine area estimated by the reanalysis data experienced on days when greater than 20 cm of snow fell at Mt Hotham, Mt Buller or Falls Creek. The left axis showing probability corresponds to the normal distribution in black, and the right axis shows the frequency of events corresponding to the coloured histogram. Vertical lines indicate the JJAS season averages for the reanalysis at 2.88 °C (purple), the A1FI 2070 CSIRO projected average at 5.67 °C (orange) and the A1B 2070 MIROC projected average at 4.27 °C (green).

on the already fragile snowfall conditions in Alpine Australia.

Focusing now on the orange and green vertical lines, which represent the A1FI (worst case emission scenario) 2070 projected average T850 by the CSRIO Mk 3.5 and the MIROC Medres models respectively, it can be seen that currently at these temperatures, whilst heavy snowfall has still been known to occur, such events are rare. This suggests that heavy snowfall events will become limited to occurring with intense synoptic events bringing heavy precipitation and cold temperatures to the region. Values for all the other projected temperatures can be seen in Table 3.

4. Discussion and conclusion

In this study a new snowfall data set has been presented for the first time. A new snow parameter (snow accumulation) is shown to be a highly effective measure of snowfall in Alpine Australia. Declining trends have been found in both the maximum snow depth, in support of recent work done by Nicholls (2009) and Davis (2013), and snow accumulation. Both are highly related to rainfall variables and maximum temperature. Interestingly, no significant correlations were found between snowfall variables and key climate drivers. This is surprising as work done by Fiddes and Pezza (2014) indicates that alpine rainfall has some relationship with the SOI and DMI indices.

With the use of daily snow depth data, a measure of the frequency of snowfall has been explored for the first time. The total number days of snowfall greater than 0 cm and those between 1 and 10 cm have been shown to be decreasing significantly, whilst days of between 11 and 20 cm and greater than 20 cm show no declining trend with time. The percentage of snow accumulation the four of these groups make up individually is not changing significantly. A more detailed analysis, using smaller bin sizes, is needed to fully understand how Australian snowfall is changing.

Future projections show that the average temperature is expected to increase by up to 3 °C by 2070 over the Alpine area. If these temperatures are to become the new climatological average, then the occurrence of snowfall events is likely to be significantly reduced and would only be observed during intense cold outbreaks, such as those described by Ashcroft *et al.* (2009) or the most intense systems found to bring snow in the study by Fiddes *et al.,* 2014. This shift in snowfall regime is found to already be occurring, with significant declines in marginal snow events being observed.

These results say nothing of the changes expected in precipitation in the area, especially extreme precipitation. Previous studies have shown that there has been an increase in the amount of seasonal rainfall attributed to extreme rainfall events over eastern Australia (Haylock and Nicholls, 2000). Furthermore, Alexander and Arblaster (2009) show that although very noisy, some proxies of extreme rainfall are projected to increase significantly with global warming. With an increase in the number of extreme precipitation events, often accompanied by cool weather in southeast Australia, the chance for heavy snowfall events to occur may also increase. Such suggestions are consistent with the finding in this study of no change to heavy snowfall events.

Work by Timbal and Drosdowsky (2013) indicates that with a strengthening of the STR (and to a lesser degree a southwards shift), the ability for weaker cold fronts to penetrate northwards over the Australian continent will decline. While only a weak link with the STR was found in this work, such a shift could have further serious impacts on light snowfalls in the Australian Alps and again suggests that snowfall may only occur as a result of the most intense cold fronts.

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