The influences of climate drivers on the Australian snow season

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(Manuscript received November 2014; accepted November 2015)

The El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Southern Annular Mode (SAM) are all widely recognised as having significant impacts on rainfall and temperatures in southeastern Australia, particularly during winter and spring. However, there has been little analysis of the year-to-year impact of these climate drivers on Australian snow depths. This paper aims to address this gap, identifying a strong decrease in snow cover throughout the winter season during years of El Niño or positive SAM, with significant changes in late winter and spring snow cover related to the state of the Indian Ocean Dipole. Temperatures are identified as the most important factor in determining the seasonal maximum snow depth, with important implications for future snow cover as a result of a strong warming trend.

Introduction

The Australian Ski Areas Association estimates that the ten mainland ski resorts in Australia increased the combined Gross Domestic Product of New South Wales and Victoria by $1.5 billion, generating $350 million in taxation revenue and more than 14,000 jobs (ARCC 2012). However, snow is relatively rare in Australia, with less than 5000 km^2 (0.15%) of the mainland experiencing regular snow cover for more than a month each year, and an average maximum natural snow cover depth of just 195 cm at Spencers Creek (1830 m), which is close to the highest elevations of existing ski fields. This results in a high sensitivity of the Australian ski resorts to interannual variations in snow cover, with a strong and statistically significant relationship between the number of ski days per year and natural snow depth (Pickering et al. 2010).

The low elevation of Australia's snow fields and the strong background warming in the Australian climate (CSIRO 2014) have motivated a number of studies of how snow occurrence is changing. Nicholls (2005) identified a 10% decline in annual maximum snow depth between 1962 and 2002, with the largest decline in spring (40%), while Davis (2013) identified that the average annual maximum snow depths were 15% lower than the 1961-1990 average during 2001-2010. This decline has occurred despite no significant changes in the average precipitation at nearby stations (Davis 2013) or the frequency of extreme precipitation events (Fiddes et al. 2014a), and appears primarily related to enhanced warming over the alpine region. The larger trends in spring come as a result of this season being more marginal, with the warming trend bringing forward the shift of snow accumulation to snow loss.

Hennessy et al. (2003, 2008) project that annual snow depth declines will continue, with the total area experiencing at least 60 days of snow cover expected to decrease by 17.5-60.3% by 2020 and 38.1-96.3% by 2050, relative to 1990 levels. The length of the ski season (days > 50 cm) is also projected to decline by at least 30% by 2050 under the low-emissions scenario at low altitude ski resorts, necessitating significant further investment in snowmaking capacity in even the most "optimistic" scenarios. More recently, Bhend et al. (2012) projected a 30-70% decline in annual maximum snow depth relative to 1990 levels by 2050 at Falls Creek and Mt Hotham, the major alpine resorts in Victoria, under a low-emissions scenario; the average maximum snow depth declines to 15-20 cm under the most severe projection for the high emissions scenario. Observed snow cover in the years since these projections were made add to the confidence of future projections, with only one year between 2005-2014 recording above-average peak snow depths at Spencers Creek and particularly poor ski conditions in 2006.

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There is a strong understanding of the influence of major climate drivers on southeast Australian rainfall and temperatures. Both El Niño and positive IOD events are associated with decreases in rainfall, with drought conditions in southeast Australia (including the Snowy Mountains) most likely during years where both drivers occur in concert (e.g. McBride and Nicholls 1983, Risbey et al. 2009, Ummenhofer et al. 2009). El Niño is also associated with increased maximum temperatures in late winter and spring, but lower minimum temperatures at lower elevations owing to clear skies and lower soil moistures (e.g. Nicholls et al. 1996, Power et al. 1998, Jones and Trewin 2000). The positive phase of the Southern Annular Mode (Hendon et al. 2007) is also associated with decreased winter rainfall in parts of southeast Australia and increased spring rainfall along the southeast coast. The alpine region lies between these two regions, which causes some uncertainty in projected precipitation impacts. However, in spring positive SAM is also associated with cooler daytime temperatures across much of southeastern Australia, which could favour increased snowfall later in the season.

Despite this understanding there has been limited investigation of how these drivers might impact Australian snowfall and the ski industry. Budin (1985) identified that five of the eight El Niño years between 1935 and 1984 were associated with very low snow depths, although correlations with the SOI were generally weak (as observed more recently by Fiddes et al. 2014b). While few later studies have investigated this relationship, it has been generally assumed that neutral ENSO and negative IOD are the best conditions for snow, with El Niño years too dry, while La Niña tends to be too warm, particularly overnight. In this paper, we seek to build on the early study by Budin (1985), as well as observed relationships between snow depths and mean sea level pressure to the south of Australia (Budin 1985, Nicholls 2005) to review the relationship between the Australian snow season and three key climate drivers – ENSO, the IOD, and SAM.

Data

The most reliable measurements of Australian snow have been maintained by Snowy Hydro Ltd, with weekly snow depths measured at three unaltered sites in the New South Wales Snowy Mountains since 1954, available at http://www.snowyhydro.com.au/water/snow-depths-calculator/. The most prominent of these is the highest elevation site, Spencers Creek, which is at an altitude of 1830 m, similar to that of the major ski resorts of the area such as Perisher Valley and Charlotte Pass. From this data, we obtained fortnightly snow depths, maximum snow depth, and season length (weeks > 50 cm). We also calculated the seasonal and June-September "snow depth-days", which can be considered the integral of the snow-depth curve – for each observation this is the number of days between observations multiplied by the average depth of the observations, summed up over the season.

Data was also available for Deep Creek (1620 m) and Three Mile Dam (1460 m). The annual snow depth-days at these sites had correlations of +0.88 and +0.78 with Spencers Creek values, with correspondingly similar relationships between snow depth days and climate influences. However, due to their elevation the snow season is substantially shorter, with only one in three years measuring maximum snow depths of at least 50 cm at Three Mile Dam. For this reason the paper will focus wholly on the more rigorous results from Spencers Creek, which better matches the conditions experienced by the alpine regions of southeast Australia and the major winter sports resorts. However, it is important to note that the major resorts of Thredbo, Mt Hotham, Mt Buller and Falls Creek all have substantial areas of terrain below 1600 m in altitude, with a maximum elevation of 1565 m at Mt Baw Baw; these lower altitude snow areas may be more heavily impacted by snowfall variability than Spencers Creek.

There are no comparable snow depth data sets for the Victorian mountains, with the best available data (Fiddes et al., 2014a) starting in the 1980s, and hence this study will focus on the New South Wales data. While Victorian seasonal snow depths would be expected to be closely correlated with those in New South Wales, extension of these results to Victoria should be done with some caution, particularly as the weather systems that produce the majority of snowfall may differ across the ranges.

ENSO and IOD state (Table 1) were drawn from the years listed on the Bureau of Meteorology's website[1] as well as recent IOD declarations. These are based on a combination of atmospheric and oceanic indicators, with IOD classifications since 1958 drawn from Saji and Yamagata (2003). Note that these classifications do not reference the start date of the event; in some cases, the ENSO or IOD event may not have become established until spring, and would be expected to have a weaker impact on the winter season. The Southern Oscillation Index (SOI) was obtained from http://www.bom.gov.au/climate/current/soi2.shtml, while SAM was represented using the Marshall (2003) index due to its longer period of record (1957-present), retrieved from http://www.nerc-bas.ac.uk/icd/gjma/sam.html. Both the SOI and

[1] http://www.bom.gov.au/climate/enso/enlist/, http://www.bom.gov.au/climate/IOD/positive/, etc.

SAM were averaged over the snow season June-September for seasonal correlations, with statistical significance calculated using a Student's t-test and assessed at the 95% level.

Daily temperature data have been retrieved from the Cabramurra temperature station from 1962-2013. This station record is of high quality and has been homogenised to remove non-climate/weather factors in the record (Trewin 2013). This station is the only long-term station in the alpine region of Australia and has been frequently used for similar studies (Nicholls 2005, Davis 2013). The Cabramurra results may not be fully representative of the alpine regions further south; Cabramurra is a very exposed site on the western side of the ranges, and its July daily minimum temperatures are less well-correlated with more sheltered sites on the eastern side of the Great Dividing Range (0.76 at Perisher Valley, 0.65 at Charlotte Pass, 0.55 at Thredbo Village[2]) than might be expected from their close proximity. (Unfortunately, none of those three sites have sufficiently long or complete temperature data sets to enable their own relationships with climate drivers to be independently assessed). Daily 9am wet bulb temperature data has been retrieved from the Omeo weather station, 40 km from the Falls Creek alpine resort; however, these data are unhomogenised and may have systemic issues.

Table 1 Table 1. List of years by Bureau of Meteorology ENSO and IOD classification, 1958-2013. Note that 1954-1956 are La Niña years and 1957 El Niño; no IOD information is available for these years.

	pIOD	*Neutral*	*nIOD*
El Niño	1963, 1972, 1977, 1982, 1994, 1997, 2006	1965, 1969, 1987, 1991, 2002, 2009	1993
Neutral	1961, 1967, 1983, 2012	1959, 1962, 1966, 1968, 1976, 1978, 1979, 1980, 1981, 1984, 1985, 1986, 1990, 1995, 2001, 2003, 2004, 2005	1958, 1960, 1989, 1992, 1996, 2013
La Niña	2007, 2011	1970, 1973, 1988, 1998, 1999, 2000, 2008	1964, 1971, 1974, 1975, 2010

The average rainfall across three high-quality sites (Lavery et al. 1992) southwest of the Snowy Mountains (Mitta Mitta, Whitlands and Beechworth) has been used as a proxy for regional precipitation. These sites have a stronger relationship with maximum snow depth than either the district average rainfall derived from the AWAP gridded product (Jones et al. 2009) or alpine rainfall stations such as Perisher Valley. This reflects issues with gridded datasets in areas of high topography, with few high-altitude stations available before the 1990s (Jones et al. 2009), as well as issues with accurate precipitation measurements at alpine sites when it falls as snow. It is not unusual for rain gauges to suffer blockages in winter due to the accumulation of ice and snow, while wind-blown snow creates additional complication for the use of the alpine records. The combination of the maximum temperature and precipitation data allows us to classify each winter as both wet/dry and warm/cold, based on whether the seasonal values were above/below the 1962-2013 median.

Throughout the paper, significance is assessed using a two-sided t-test, with results reported at the 95% confidence level unless otherwise stated.

Results

The influence of climate variables on snow depths

Prior to assessing the relationship between snow depth and climate drivers, it is useful to reassess the relationship between snow depth and both precipitation and temperatures in alpine regions. As previously observed in Nicholls (2005) and Davis (2013), the correlations between maximum snow depth at Spencers Creek and both mean winter maximum temperature at Cabramurra and alpine-region precipitation are strong and similar in magnitude, reflecting a similar contribution from both factors. Using the 1962-2013 period from this paper, the correlation coefficients are -0.61 and +0.63 respectively,

[2] Correlations are taken over the period of parallel record between the named sites and the 1962-1999 Cabramurra site. The listed correlations can be compared with those between Cabramurra and similarly exposed Victorian sites, Falls Creek (0.84) and Mount Hotham (0.83).

with a weaker correlation between snow depth and minimum temperatures (-0.36). These relationships have been used in previous papers to derive linear regressions to extend the snow record (Nicholls 2005; Davis 2013).

Both above-average seasonal precipitation and below-average temperatures are necessary prerequisites for heavy snow seasons (Figure 1); of the 10 years with snow depths greater than 250 cm, all but two had both below-median temperatures and above-median precipitation, with the remaining two years very close to median for the absent factor (-0.6 mm and +0.2°C respectively). Warm weather seems to have a slightly stronger impact on seasonal snowfall than below average precipitation, with average seasonal snow depths of 172 cm during wet, warm years compared to 187 cm during cold, dry years, although these differences are not significant. Maximum temperatures also have a substantially larger correlation with the season length (-0.43) than the mean precipitation does (+0.26) , reflecting a particularly strong relationship between temperature and snow depth in late September and early October, consistent with results in Nicholls (2005).

This result is of particular importance given ongoing warming over the coming century, with 19 of the past 21 years having winter temperatures at Cabramurra above the long-term median. The warming trend is most noticeable in September, where the 2000-2013 average maximum temperature at Cabramurra was a remarkable 2.2°C above the average of all previous years with data available (1962-1999). The Australia-wide mean maximum temperature was 1.2°C above average using the same base period. Nation-wide, temperature anomalies during the last decade are higher for September than for any other month, followed by August, July, and October.

Figure 1 The total number of seasons with Spencers Creek maximum snow depth in various categories for winter mean maximum temperatures and total precipitation above or below the 1962-2013 median. The number of years in each snow depth category is indicated in parentheses; note that the warm/dry and cold/wet combinations (N=15) are more common than wet/warm or dry/cold (N=11)

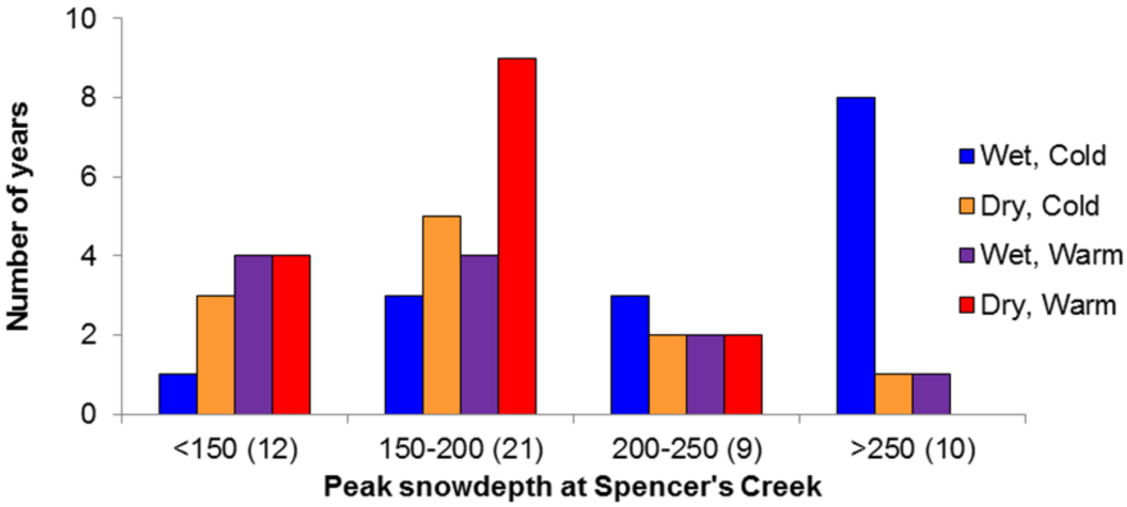
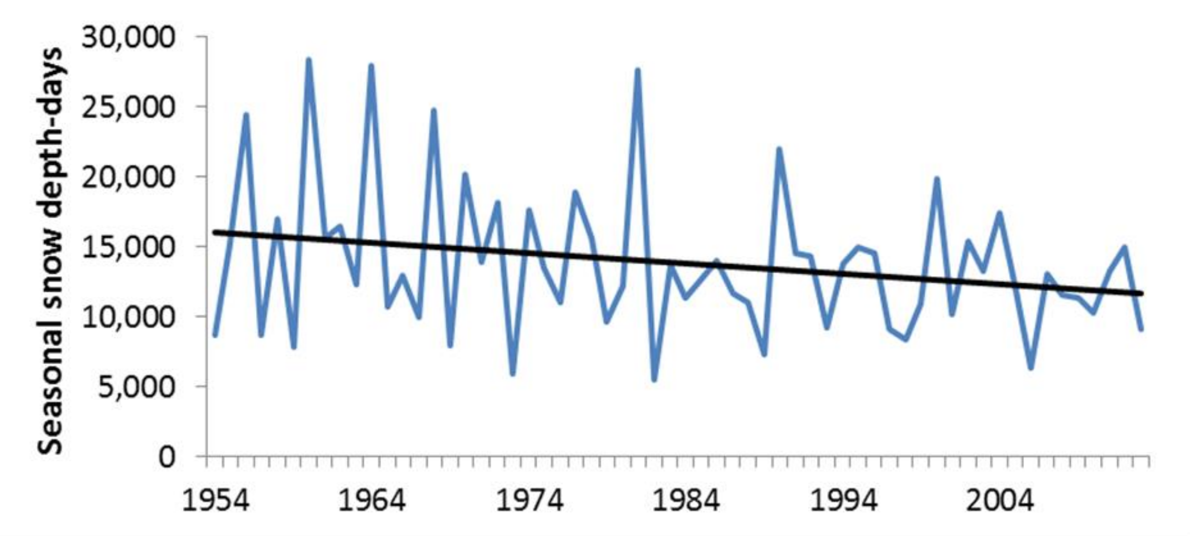


Figure 2 Annual June-September snow depth-days (cm-days) at Spencers Creek, 1954-2013, with a linear trend line shown.



The increase in alpine temperatures is associated with a 10% decline in the average maximum snow depth and a 5% decline in the length of the snow season during the 2000-2013 period relative to 1954-1999, with largest declines in snow depths in late September (-18%) and early October (-30%). This is particularly evident in a lack of heavy snow seasons in recent years, with a 10% decline in June-September snow depth-days associated with an absence of any seasons with depth-days above 20,000 since 1990 (Figure 2). It may also be associated with a shift in the date of peak snowfall; this was 11 days earlier during 2000-2013 than 1954-1999, with 2011 and 2014 the first snow seasons on record to observe peak snow depths during July.

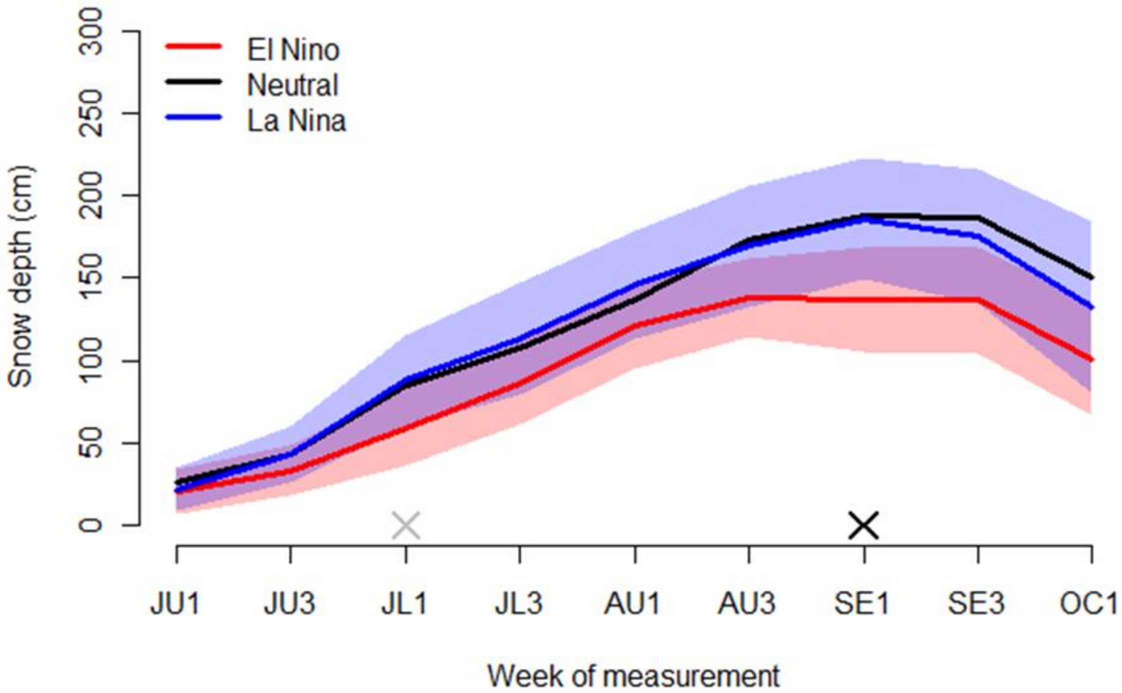
It is important to note that, as observed in Nicholls (2005), using temperature alone as a predictor tends to overestimate observed trends, in part because individual heavy snow events are a large contributor to seasonal totals, which depend not only on the presence of precipitation but also its timing and relationship with prevailing temperatures. These heavy events may also be less impacted by changing temperatures than lighter snowfall is (Fiddes et al. 2014b). Furthermore, winter rain events associated with above zero temperatures can decrease snow depths, as observed during the early winter of 2013. However, daily snow depth data is of lower reliability and is only available from ski resorts (Fiddes et al. 2014b), limiting the potential for analysis of heavy snow events or significant snowmelt events.

The influence of climate drivers on snow depths

As observed in previous studies (Fiddes et al. 2014b), correlations between seasonal SOI and the length of the snow season are not statistically significant, with only weakly significant correlations between SOI and maximum snow depth (+0.29), despite strong relationships between ENSO and both rainfall and temperature in southeast Australia (e.g. Risbey et al. 2009, Power et al. 1998). This appears to reflect a distinct nonlinearity in the relationship between ENSO and snowfall – while the maximum snow depth is, on average, 23% lower during El Niño years than in neutral years, there is little discernible difference in snow patterns between La Niña and neutral seasons (Figure 3). For this reason, while the decline in El Niño years relative to neutral years is statistically significant for both maximum snow depth and weekly snow depths from late August onwards, the difference between El Niño and La Niña years is generally not significant.

The tendency for El Niño years to see less snow is apparent across the snow season but particularly from mid-August onwards, with September snow depths 28% lower in El Niño years and early October snow 34% lower, resulting in a 25% decrease in total snow depth-days. This is consistent with well above average maximum temperatures during the August and spring of El Niño years in Cabramurra (+ 0.8°C) and much of eastern Australia (Figure 4); the influence of ENSO on early winter maximum temperatures at Cabramurra is minimal.

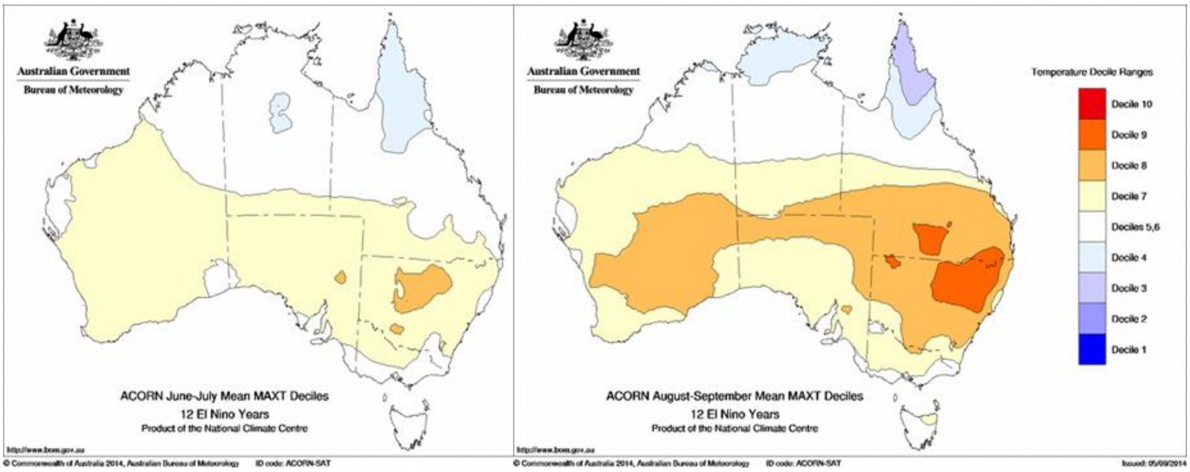
Figure 3 Fortnightly average snow depths in El Niño, La Niña and Neutral years, 1954-2013, with the 90% confidence interval about the mean indicated for the El Niño and La Niña periods (as calculated using a t-test). X-axis indicates the week, with JU1 the first week of June, JL3 the third week of July, etc. More precise dates are unavailable as the actual dates of snow measurement differ between years. Grey crosses above the X-axis indicate weeks where the difference between the means in El Niño and La Niña years is statistically significant at the 90% level using a two-sided t-test, with black crosses indicating where the difference is statistically significant at the 95% level.



This is an interesting contrast to results for low elevation sites. In a study of 53 years of snowfall data between 1949 and 2001 at Bukalong (790 metres elevation), near Bombala, Hague and Trewin (2014) found that snowfall was suppressed in La Niña years, but that there was no clear difference between El Niño and neutral years once two extreme years, 1949 and 1987 (the second of which saw 104 centimetres fall in a single event), were removed from consideration. It is not unexpected that low-elevation sites may have different relationships with large-scale drivers than Spencers Creek, with individual heavy events of much greater importance at lower elevation sites where snow is infrequent. Importantly, while some years with notable low-elevation snowfalls, such as 2000, have had above-normal seasonal accumulations at Spencers Creek, others, such as 1965, have been below normal at high elevations. The results in this paper for other drivers can therefore be applied to high altitude alpine sites only.

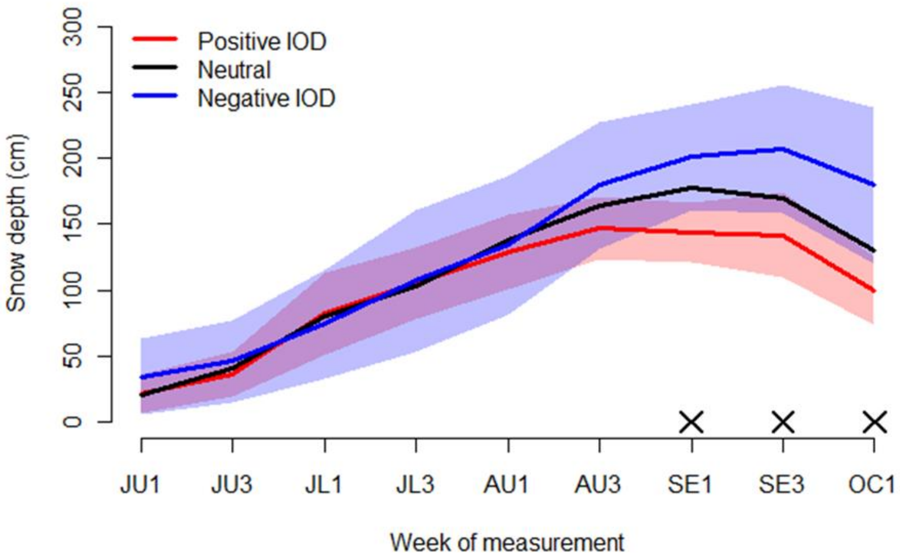
The nonlinear impacts of ENSO may be a relatively recent phenomenon. When the database was divided into two 30-year periods (1954-1983 and 1984-2013), both periods showed declines of 20-30% in peak snow depth in El Niño years. However, while La Niña years in 1954-1983 had peak snow depths 10% higher than neutral years, during 1984-2014 both La Niña years (-20%) and El Niño years (-25%) showed similar declines in average maximum snow depths relative to neutral years. The significantly larger changes in snow depths during La Niña years relative to other periods is an area in need of further study, and may have serious implications for the future prevalence of “good” snow seasons. However, the short length of reliable snow records in Australia makes it difficult to examine temporal changes in the ENSO-snow relationship with any robustness.

Figure 4 Composite June-July (left) and August-September (right) maximum temperature deciles for strong El Niño years, 1900-2012. For further details and composite plots see http://www.bom.gov.au/climate/enso/ninocomp.shtml



The Indian Ocean Dipole was found to have slightly stronger relationships with peak snow depth than the SOI by Fiddes et al. (2014b), with a correlation of -0.35 between the Dipole Mode Index (an index of the IOD) and total snow accumulation. The IOD appears to only have a strong influence on late August and spring snow cover (Figure 5), reflecting the tendency of IOD events to emerge during late winter and early spring. Maximum snow depths with positive IOD are 26% lower than negative IOD years, but snow depths later in the season are 44% lower (in early October), with snow depths significantly different from early September onwards. Correspondingly, the total snow depth-days in positive IOD years are 14% lower than neutral years, and 24% higher in negative IOD years. The IOD is also a major contributor to the most significant snow years, with 58% of negative IOD years recording at least 200 cm of snow.

Figure 5 As in Figure 3, but for positive, negative, and neutral IOD years, 1958-2013.



Temperature impacts again appear to have a strong influence on snow depths, with August-September temperatures at Cabramurra 0.8°C above the 1962-2013 average in positive IOD years, and 0.8°C below average during negative IOD years. In contrast, despite the strong link between both phases of the IOD and winter-spring rainfall across southeast Australia (e.g. Risbey et al. 2009), across our three-station series the June-September rainfall during positive IOD years is 36% lower than neutral years, compared to just a 9% increase in rainfall during negative IOD years.

Surprisingly, although Victorian winter-spring rainfall is significantly enhanced with both drivers in the wet phase (e.g. Risbey et al. 2009), the interaction between ENSO and the IOD has little impact on maximum alpine snow depths (Table 2) or on total snow depth-days (not shown).This may be related to distinctly different nonlinearities in the impacts of these drivers on maximum temperatures and rainfall, both of which have correlations of ~0.6 with maximum snow depth. While the combination of La Niña and negative IOD is associated with distinctly lower maximum temperatures than either event individually, there is no corresponding enhancement of rainfall, while the opposite pattern is observed for the El Niño/positive IOD combination (larger dry anomalies, no change in temperature anomalies).

Table 2 Average peak snow depth at Spencers Creek (cm) across combinations of ENSO/IOD years, 1958-2013, based on years in Table1. Results are not shown for groups with less than three years (*). Note that due to the small sample sizes, none of these means are significantly different from each other or from the all-years mean at the 95% level.

	pIOD	*Neutral*	*nIOD*
El Niño	162.9	168.7	*
Neutral	179.7	208.9	234.3
La Niña	*	180.6	240.8

There is a clear, though not significant, decrease in both maximum snow depths and total snow depth-days during La Niña years in the absence of a negative IOD event. This is largely a result of temperature variations, with an average maximum temperature anomaly of +0.6°C when La Niña is combined with neutral conditions, or -0.9°C when combined with negative IOD conditions; the average maximum temperature across all La Niña years is close to average (+0.15°C). It is also worth noting that the only two years with maximum snow depths below 100 cm (1982 and 2006) featured both El Niño and positive IOD. Both of these years were extremely dry in the broader region, with 1982 the driest winter in the 1954-2013 period for the three high quality rainfall sites. Additionally, 1982 and 2006 were the two driest June-September periods within the years 1954-2013 at seven selected long-term rainfall stations on the northern and western side of the Alps.

The Southern Annular Mode is closely related to the positioning of the midlatitude westerlies, with positive SAM associated with decreased rainfall in parts of southeast Australia during the winter months (a southerly shift in midlatitude westerlies), as well as increased maximum temperatures during spring (Hendon et al. 2007). The June-September SAM has statistically significant correlations with the maximum snow depth (-0.42), snow season length (-0.32) and snow depth-days (-0.41), with strongest correlations during the second half of the season. This is not surprising, as Nicholls (2005) found a very strong relationship between snow depths at Spencers Creek and seasonal mean sea level pressure to the south and east of Australia, while Budin (1985) observed very strong relationships between Spencers Creek snow depths and the mean position of the subtropical ridge.

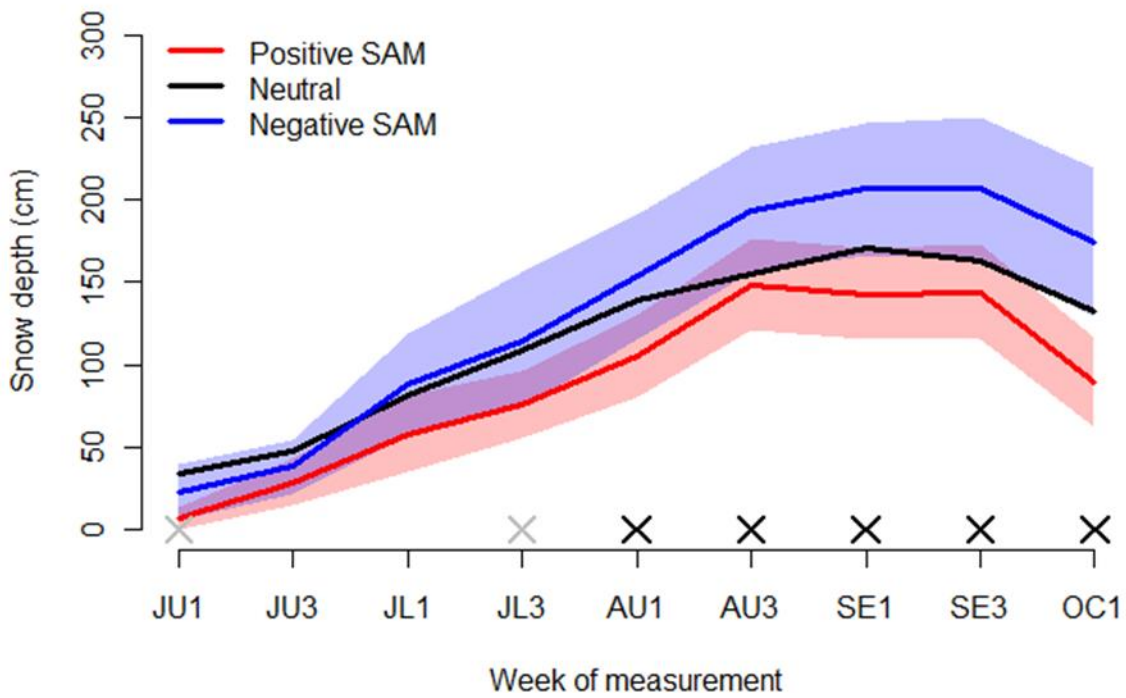
For consistency with the frequencies of ENSO events and to better allow comparison between the different drivers, we define a positive (negative) SAM season by average SAM values above (below) 0.7, giving 50% of years classified as neutral years and 25% in each of positive and negative SAM. Using these definitions, the impact of SAM is slightly stronger than IOD, with average maximum snow cover in positive SAM seasons 32% below that in negative SAM, and total snow depth-days 42% lower. This difference between the two SAM phases results from a substantial decrease in early season snow cover in years with positive SAM, and a substantial increase in late-season snow during negative SAM (Figure 6), with mean snow depth significantly different from early August onwards.

SAM is substantially more variable on a weekly and monthly basis than other climate drivers, with 30% of June-September periods including both a month with SAM above 1.5 and one with SAM below -1.5 (17% using a threshold of 2), suggesting that fortnightly or monthly SAM may be a better indicator of snow depth changes. However, correlations between monthly SAM and fortnightly changes in snow depth are only statistically significant during June and early July, in contrast to the strong relationship between seasonal SAM and late-season snow accumulations, while the difference in the average fortnightly accumulation between positive and negative SAM months is only statistically significant during the first week of July.

Despite these observed relationships, no combination of indices is a guarantee of a good or bad snow season. The combination of strongly positive SAM (+1.5) and positive IOD still resulted in an above-average peak snow depth during 2012

(216 cm) despite dry conditions across much of southeast Australia, while a very poor snow year in 1988 (maximum depth 131 cm) featured both a La Niña and negative SAM (-1.78).

Figure 6 As in Figure 3, but for JJAS SAM >= 0.7, <=-0.7, or neutral, 1957-2013.



The relationship between climate drivers and the potential for artificial snowmaking

Artificial snowmaking has formed an increasing part of ski industry planning during the last decade. Artificial snowmaking is typically employed between May and August, and requires wet bulb temperatures of -2°C or lower (Colin Hackworth, Snow Australia, pers. corresp.), with cool, clear nights such as in El Niño years potentially improving snowmaking capacity. While there are no long-record alpine sites with wet bulb humidity probes, at Omeo (685 m) unhomogenised 9am wet bulb temperatures are available from 1957, 40 km from an alpine hourly data site (Falls Creek, 1765 m, 1991-2014). During the overlap period (2007-2013), the correlation between the May-August numbers of days with 9am wet bulb temperatures ≤ 5°C (WB5) at Omeo and the May-August number of hours below -2°C at Falls Creek is 0.87, allowing it to be used to extend the snowmaking record.

Between 1957 and 2013, there is a negative correlation (-0.38) between WB5 and the June-September SOI, and a positive correlation with the June-September SAM (+0.34). These are of the opposite sign to correlations for the maximum snow depth, although the correlation between WB5 and peak snow depth is not statistically significant. Additionally, there are no statistically significant relationships between either the mean June-August minimum temperature at Cabramurra or the number of cold nights below 0°C or -2°C with either ENSO or SAM.

While the Omeo data may suffer from inhomogeneities, and the Cabramurra site may not be fully representative of the alpine region, these results suggest that there is significant potential for artificial snowmaking to ameliorate the impacts of poor natural snow cover regardless of the states of major climate drivers. This is supported by limited "snowmaking minutes" data that was provided by Perisher resorts for 2004-2013. While noting this dataset is too short for detailed analysis, during these years the observed snowmaking minutes in El Niño and La Niña years were indistinguishable from those in neutral years, and the two poorest snowmaking years were 2011 (positive IOD) and 2013 (negative IOD). However, there was a correlation of +0.62 between snowmaking minutes and the June-September SAM, with positive SAM potentially aiding artificial snowmaking as well as decreasing natural snowfall.

Conclusions

The Australian ski industry and alpine environment is highly sensitive to variations in snow cover, with maximum snow depths at Spencers Creek ranging from 361 cm in 1981 to 85 cm in 2006. Particularly in the context of ongoing declines in both the maximum snow depth and the ski season length, including a 10% decline in the 2000-2013 maximum snow depth at Spencers Creek relative to 1954-1999, it is of relevance to assess the climatic factors that affect both peak snowfall and season duration.

The relative impact of ENSO, IOD and SAM conditions can be easily compared due to the relatively similar frequency of events, with the SAM state in this paper defined such that 25% of years fall into each of “negative” and “positive” conditions. At Spencers Creek, the seasonal mean Southern Annular Mode has the strongest impact on the snow season. In years with June-September average SAM greater than 0.7, the maximum snow depth is 32% lower than under negative SAM and the snow season is four weeks shorter than neutral years, both of which are statistically significant at the 99% confidence level. This is consistent with previous studies such as Nicholls (2005) and Budin (1985), who observed very strong relationships between seasonal maximum snow depths at Spencers Creek and mean sea level pressure to the south and east of Australia. The Indian Ocean Dipole also has a significant impact on snow depths during September and early October as well as on the seasonal maximum depth, but has little impact in the early- to mid-season.

Interestingly, while El Niño is associated with decreases in snow cover throughout the season, there is no discernible improvement in the ski season during La Niña years; indeed, in La Niña years without a coincident negative IOD event both the maximum snow depth and the total snow depth-days decline relative to neutral years. This is likely related to the role of both precipitation and temperatures in influencing the impact of individual snowfall events, as the increased precipitation during La Niña events may fall as either rain or snow depending on ambient temperatures. This may be a recent phenomenon, with La Niña events during the earlier period 1954-1983 associated with slightly above average maximum snow depths, and is in need of further research.

To summarise, the interplay between snow depth and climate drivers is significant, but favourable drivers do not necessarily result in above average snowfall. This reflects a strong relationship between annual snow depth maxima and the timing of individual heavy snow events as well as the type of precipitation which falls (e.g., rain versus snow), with reliable daily snow data required to better understand this relationship. Importantly, conditions favourable for artificial snowmaking have different relationships with major climate drivers compared to those desired for natural snow conditions. This therefore gives capacity for artificial snowmaking to enhance total snow depths, under conditions which are less favourable for natural snow falls, potentially providing some buffering for ski industry operators.

Acknowledgments

The authors would like to thank Colin Hackworth and the Australian Ski Areas Association for providing snowmaking information, as well as David Jones, Paul Gregory, Neville Nicholls and one anonymous reviewer, whose reviews and comments have significantly improved the quality of this paper.

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